

A Lunar Surface System Supportability Technology Development Roadmap

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This paper discusses the establishment of a Supportability Technology Development Roadmap as a guide for developing capabilities intended to allow NASA's Constellation program to enable a supportable, sustainable and affordable exploration of the Moon and Mars. Presented is a discussion of "supportability", in terms of space facility maintenance, repair and related logistics and a comparison of how lunar outpost supportability differs from the International Space Station. Supportability lessons learned from NASA and Department of Defense experience and their impact on a future lunar outpost is discussed. A supportability concept for future missions to the Moon and Mars that involves a transition from a highly logistics dependent to a logistically independent operation is discussed. Lunar outpost supportability capability needs are summarized and a supportability technology development strategy is established. The resulting Lunar Surface Systems Supportability Strategy defines general criteria that will be used to select technologies that will enable future flight crews to act effectively to respond to problems and exploit opportunities in a environment of extreme resource scarcity and isolation. This strategy also introduces the concept of exploiting flight hardware as a supportability resource. The technology roadmap involves development of three mutually supporting technology categories, Diagnostics Test & Verification, Maintenance & Repair, and Scavenging & Recycling. The technology roadmap establishes two distinct technology types, "Embedded" and "Process" technologies, with different implementation and thus different criteria and development approaches. The supportability technology roadmap addresses the technology readiness level, and estimated development schedule for technology groups that includes down-selection decision gates that correlate with the lunar program milestones. The resulting supportability technology roadmap is intended to develop a set of technologies with widest possible capability and utility with a minimum impact on crew time and training and remain within the time and cost constraints of the Constellation program

I. Introduction

NASA's Constellation Program is involved in ongoing development of Lunar Surface Systems Architecture that ultimately is aimed at establishing a Lunar Outpost capable of sustaining long-term occupation by human crews. The NASA Exploration Technology Development Program (ETDP) and the Supportability, Operability, and Affordability (SOA) Office jointly funded a multidiscipline study that examines the technology required to achieve a supportable and sustainable lunar program. Supportability, Operability, and Affordability are aspects of the

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program that are difficult to quantify in the development stage yet ultimately will affect the overall cost of the program once facilities are established and operational.

NASA is currently developing new vehicles with multiple goals of reducing the human risks and cost of space flight while expanding the reach of human exploration. Launch costs are ultimately applied to the payload delivered and this study considers technologies that extract the highest possible utility from these payloads in lunar operations. This technology roadmap attempts to identify needs, define the capabilities and identify candidate technologies that will be developed. This roadmap is focused on Lunar Surface Systems (LSS) maintenance, repair and related logistics of supportability. This study considers lessons learned from NASA flight operations, NASA logistics depot experience and lessons learned from military flight systems.

The initial effort was to characterize existing space based maintenance and related ground support for the International Space Station (ISS). For the ISS the maintenance strategy is to remove and replace modular Orbital Replacement Units (ORU)¹. This approach was adopted primarily due to constraints on crew time and the need to return systems to full function and restore redundancy as quickly as possible. The approach envisioned by ISS would have been supported by a robust logistics infrastructure with re-supply intervals, as short as every few weeks. In contrast, NASA's planning for a lunar outpost currently assumes only 3-4 missions per year with 2 crewed and 1-2 cargo missions.^{2,§} The payload delivered by an expendable cargo vehicle to the lunar surface is roughly 22% of the payload the same vehicle would deliver to ISS in low Earth orbit³. This puts further pressure on the program to design payloads with high utility to match the higher payload cost. Unlike the ISS, lunar hardware is not part of a closed-loop logistics transportation cycle. The ability to return hardware, repair it and re-launch it was based on the Space Shuttle's massive capability to move hardware between Earth and orbit in both directions. For lunar missions, the roughly five fold increase in payload delivery cost, the one-way transportation of hardware, and the dramatically reduced frequency of launches drives a need for a new supportability strategy.

Recently, NASA's Lunar Surface Systems (LSS) program began considering concepts to extend repair capabilities to surface operations, where crew members and robotics may perform repairs and routine maintenance. This may involve removing Lunar Replacement Modules** (LRU), de-integrating assemblies, diagnosing and repairing at the sub assembly and component level, followed by, functional test and re-integration steps and finally returning the hardware to service. This represents an unprecedented level of complexity and potential risk if improperly executed. However, it also represents an unprecedented capability and flexibility that empowers the crew to act effectively in response to problems. This is a major paradigm shift for a NASA space missions and must be carefully considered in the lunar architecture.

Many of supportability technologies needed to enable this level of maintenance will be embedded in the actual flight hardware to assure that hardware is accessible, serviceable and even scavenge-able. Therefore the technology must be defined early and infused into the spacecraft design. Many of supportability technologies represent new process technologies that can operate in an extremely resource scarce environment where conventional technologies are inoperable. Like ISS, the lunar outpost will be required to minimize the demand for crew time and crew training. Therefore, this roadmap also considers the operational context and the need for ground support of the crew to assure that maintenance operations are effective, safe and do not pose risks to the crew or systems.

II. On Orbit Supportability Strategies and Lessons Learned

The following section examines some of the past and current practices for supporting the logistics and repair needs of space flight missions. The discussion will begin with a look at previous missions, including Apollo, Skylab, and Mir. The discussion will then focus on current practices and lessons learned from the Space Shuttle and the International Space Station. Additional insight to maintainability based on military experience and lessons learned was provided by Department of Defense contributors.

A. Apollo Era On-Orbit Maintenance

The experiences of the Apollo, Skylab, and Mir missions point out the occurrence of and recovery from faults and failures. Due to the short mission duration, the primary strategy for major failures during an Apollo mission was to abort the mission and return to Earth. The events of the Apollo 13 mission illustrate this plan. Other Apollo missions experienced far less critical faults and failures, including a damaged television camera, a failed potable water tank valve, and damage to a lunar rover fender. In these cases the crew used redundant systems operated at a reduced capacity, or in the case of the damaged fender, scavenged from materials on hand to repair the damage (in

[§] Recent schedules indicated mission frequency of 2 per year.

** Lunar Replacement Unit (LRU) and Orbital Replacement Unit (ORU) are equivalent assemblies

this case, using lunar surface maps clipped in place as a replacement fender). Determining the fault in the case of the television camera and valve required post flight inspection and testing of identical equipment to determine the root cause of the failures. The later Skylab missions suffered from damage incurred during the initial launch, reducing the vehicle's capacity to manage heat and generate power. The first two crews performed repairs allowing Skylab to operate, and demonstrated the capability of crews to perform repairs and recover from potentially major faults or failures.

B. Russian Mir Strategy

In the case of the Mir station, the Russian Space Agency (RSA) planned for a high degree of crew involvement in repairing and maintaining the vehicle's systems. The Russian general maintenance philosophy used on the Mir station is still in use on the Russian Segment of the ISS. The philosophy has been characterized by the phrase, "Run it until it breaks"⁴. This should not be interpreted as lack of preventative maintenance, but rather that hardware is operated until it reaches its end-of-life without preemptive maintenance. Cosmonauts replace faulty hardware if a replacement is available, or would find a way to diagnose and repair the system or operate with a degraded system until a replacement could be provided. In lieu of a spare, the crew is permitted to cannibalize other system's hardware at the expense of redundancy depending on donor system's criticality. Replacements may be manifested on the next available flight but there is an emphasis of repairing the system at hand. The crew work load increased as Mir continued operations well past its expected lifetime. From March 11, 1995 to May 31, 1998 cosmonauts performed 137 maintenance activities, some major, and all were successful in replacing, repairing, or working around the fault⁴.

Unlike the American approach, Russian approach does not appear to have a heavy dependence on logistics and modular Orbital Replacement Units (ORU). The Russian approach places emphasis on the crew's roles and responsibility for spacecraft maintenance. They depend less on sophisticated technologies and depend more on diagnostic and repair skills of the crew. In the Russian approach, the crew has much more latitude to determining a course of action and has demonstrated resourcefulness in the diagnosis and repair of problems. The approach is more consistent with a "resource scarce" environment where the installed hardware has an intrinsically high value and worth the effort to repair in-situ. This is in contrast with the American approach where crew time is highly valued and focused on mission objectives and faulty hardware is expendable. There is no right answer, but rather a trade off based on the expected spares availability and the crew time availability for maintenance.

C. The ISS On-Orbit Maintenance (OOM) Philosophy

The ISS philosophy is to use available resources to maintain, repair and replace failed ISS hardware components and return the affected systems to their original configuration and efficiency. NASA's baseline approach for the ISS is to remove and replace defective ORUs in their entirety. This approach is based on the idea that replacing ORUs requires less crew training and reduces the amount of crew time required to make repairs, thus increasing the amount of time to perform science activities. In limited cases, where time considerations and the lack of a spare ORU do not permit replacement, repairs are made to a part of an ORU. This repair philosophy also requires cooperation from the international partners (IP). This includes the planning, training, and execution of repair procedures, and providing repair kits including unique tools and parts. The sharing of tools between partners is expected, and all affected partners must agree on a plan that calls for scavenging from one system to restore functionality to another.

Eleven years of operation have provided insights into supportability operations and lessons that can be applied to the next generations of vehicles and missions. NASA should include maintenance and reliability requirements in contracts to build parts, systems, and vehicles, and define an Integrated Logistics Support (ILS) process, and develop a Maintenance and Operations Concept (MOC) early in the design phase. An ILS manager should have a senior position in a project, and logisticians should be assigned to design teams as a resource (not a designer) for reparability and maintenance concepts. Designs should stress commonality of parts, components, fasteners, etc., to the greatest degree possible, and decide on a single system of measure (i.e. metric or English), and design with reparability and robustness of the finished parts and systems in mind. Missions should also be provided with a comprehensive set of tools to allow for maintenance and repair, and provide tools for testing system or part performance, diagnose faults, and verify a repair before returning a part or system to service.

D. ISS Flight Operations Lessons Learned: Tools & Equipment Recommendations

- Enforce Common Fastener and Tools
- Eliminate recurring calibration cycles and integrated calibration features
- Common IVA & EVA Tools
- Minimize impact of additional Component Level Tools Set

- Go 100% Metric
- Durable portable tool storage & caddies with improved user friendliness
- Logistics must account for consumable bit, blade and die breakage (and extraction)
- Provide a wide range of portable visual magnification
- Avoid process containment that reduces user access and visibility
- Reduce or Eliminate need for Post Repair Certification

E. ISS Flight Operations Lessons Learned: Programmatic Recommendations

- Provide Integrated Logistics Support (ILS) education down to sub contractors
- Logistics and supportability must be a designer responsibility
- Track logistics requirements and review them at project design milestones
- Establish “Maintenance Operations Concept” early
- Enforce explicit availability, maintainability requirements (Use “Shall”)
- Anticipate obsolescence: Anticipate loss of key vendors, acquire plenty of spare components early
- Build In-house component level capability and skills for long term
- Maximize opportunities to add robustness (life margin) to minimize life cycle costs.
- Provide incentives for Supportability that match size weight & power incentives
- Centralize design and operations information with comprehensive search capability

F. Lessons Learned from the Department of Defense

The experiences of U.S. Navy NAVAIR group with military aircraft, also contribute lessons learned and concepts to use in future vehicle development and operation. One important aspect is the “testability” of a system. Designers must provide a Built-In-Test (BIT) which includes fault isolation to the component level to provide faster diagnosis and insight into the root cause of a fault.

In addition, designers must provide tools and processes to test the operation of a system, isolate faults, and perform post repair tests to determine the success of the repair. The design for testability must take balanced approach between BIT and external capabilities. BIT tests are useless when the electronics are rendered inoperable due to power or communications outage. External equipment is still needed to pick up where BIT capabilities fail. Therefore, testability still requires external equipment, tools and corresponding crew training.

The NAVAIR experience also includes managing contracts and relationships with outside contractors or vendors. Contracts must be written to incorporate new technologies and testability functions. The maturity of technology, as well as lack of incentive, can lead a prime contractor to forego integrating in testability. The testability and supportability concepts should also be encouraged as a cost saving measure for the contractors, by reducing testing and maintenance costs, and positively affecting their balance sheets, as well as improving the supportability of the end product for the end user.

III. Lunar Capability Considerations per ISS Operations and NASA Depot Experience

The following sections summarizes the considerations and the issues of extending Earth based depot capabilities to a notional "lunar depot" facility. These considerations and recommendations were provided by NASA Logistics Depots currently supporting the Space Shuttle and the International Space Station. Because of the constraints on crew size and logistics, some extraordinary and innovative techniques may be needed to allow Earth based depots to support a lunar depot.

A. Crew Operations and Equipment Considerations

Interactive Multi-media for Crew Skills Consideration: Crew training, Earth technical support, and interactive multi-media (including interactive 3D visualizations of assemblies, drawings, processes) capability is needed to provide in-situ familiarization and refreshing knowledge and skills prior to performing repairs. Crews must have acquired skills to handle maintenance at multiple levels (LRU, SRU, and component level) including, disassembly & reassembly, diagnostics, and repair. Repair skills are required for various component level fault isolation including removal and replacement. Furthermore, crews must be provided with multi-media training in the operation and maintenance of test equipment at LRU and SRU level.

Equipment Calibration Consideration: The lunar depot must consider equipment and tool calibration capability to ensure that all measurements remain true and within their specified tolerances. On Earth, calibration is governed by

the science of Metrology and is performed hierarchically by calibration and standards laboratories throughout the United States and the World. In a constrained lunar environment, a self sustained Metrology processes (calibrations) must be incorporated in the design of equipment and measurements as much as possible so as to minimize or eliminate the transportation of equipment back-and-forth to Earth. The use of fundamental and primary standards now performed at Primary Standards Laboratories (PSL) along with innovative techniques in traceability may be required to be performed within the lunar environment to accomplish the calibration objectives.

Repair Process Materials Consideration: Repair processes often require chemicals with special containment requirements and limited shelf life. Lunar Depot operations must develop innovative materials and processes that simplify storage and containment requirements.

Problem, Corrective Action and Configuration Management: A lunar depot will need an automated means of managing the overall process of responding to problems, preparing procedures, recording and maintaining quality control records and tracking the configuration of individual items including post repair configuration. This means will include synchronizing information between the lunar depot and Earth based logistics support centers.

Root Cause Analysis Consideration: Supportability will need the capability to perform Materials & Process evaluations and failure analysis support for root cause determination of hardware failure. The capability must deal with the problem that there is no practical way of returning faulty hardware for analysis. Fault and root cause evaluations will become increasingly important to understand and prevent repeated occurrences.

B. Flight Hardware Design Considerations

The NASA Depots also advised that the flight hardware should be designed in a manner that embeds capabilities or enables in-situ repair to reduce the dependence on external equipment.

Hardware Commonality Consideration: Past projects considered commonality primarily from a program life cycle cost issue. For LSS, however, commonality is required to make in-situ component level maintenance and repair viable. It is also essential if scavenging of spares from spent flight hardware is used as a logistics strategy. Electronics module commonality allows a mid-level electronics design to be used in multiple applications (Exp. Pyrotechnic Initiator Controller) and supported by a common set of diagnostic and repair tools. Electronic component and specification commonality reduces the number of component spares and also allows components to be scavenged. Connector/Interface and harness commonality can minimize the quantity and variety of special tools, contacts and spare parts. Mechanical fasteners and hardware commonality reduces tools and spares, but also simplifies assembly operations with fewer tool changes. Avoid custom single purpose equipment and utilize common standard test equipment such as oscilloscopes, meters, analyzers, and tools such as torque wrenches, etc

Manufacturing Materials and Process Consideration: Judicious use of materials and innovative design techniques in manufacturing will be required to facilitate maintenance and repairs in the lunar environment. Manufacturing materials and the processes selected need to assure reparability. The method of manufacturing and use of materials can restrict or prevent the repair of components. Earthbound repair processes often require materials and chemicals with special containment and limited shelf life. When materials need to be re-applied consider easy-to-apply substitutes that reduce complexity and the need for process containment.

Embedded Capabilities Consideration: The extent of equipment needed for lunar maintenance and repair and the overall viability of in-situ supportability depends on embedding the Diagnostics, Repair and Test in the original design. Hardware needs to embed design features that assure ease of access and simplify disassembly and reassembly. Designers can improve the feasibility of SRU or component level repair by embedding capabilities that would minimize the external test equipment, adapters, fixtures, hookup cables, tools and related crew training. For electronics this includes embedding repair capability by incorporating test points, diagnostic connectors, and self diagnostics software designed for troubleshooting to the component level.

Delta Acceptance Test Consideration: Design flight hardware to limit the degree of revalidation and re-testing (delta acceptance test) required for repairs. Where possible, design to minimize the need for Validated Test Set and employ standardized repair procedures. Fault tolerant electronics must provide fault isolation to minimize external or subsystem damage caused by a LRU/SRU failure. This system fault isolation capability should also be extended

to protect the system and permit in-system LRU checkout of repaired hardware. This reduces the need for dedicated external test equipment and interface emulators.

C. NASA Depot Recommendations

To accomplish practical supportability goals in lunar operations requires multiple approaches:

- Eliminate or minimize repair equipment complexity
- Employ practical, versatile and innovative materials and process technologies
- Self calibrations, innovative traceability and fundamental reference standards
- Empower the crew with interactive 3D multi-media for in-situ or real time training support.
- Provide telecommunication and information infrastructure that links Earth based Flight and Depot Operations with LSS for: failure analysis, corrective action instructions, root cause analysis and configuration management
- Elevate hardware commonality as critical to LSS supportability (beyond cost saving)
- Design and manufacturing hardware for self sustainability (low logistics needs)
- Embedded capabilities where ever practical to minimize external equipment.
- Develop innovative delta acceptance test techniques that permit in system ORU testing.

D. NASA Depot Mean-Time to Repair data.

The NASA Shuttle Logistics Depot (NSLD) and the NASA Spacecraft Services Depot (NSSD) provided estimates for labor hours required to repair various types of on-orbit hardware. Only a portion of the ISS ORUs are processed in these facilities. The estimates were based a mix of space shuttle and space station hardware. The data is usable for considering the general types of repairs performed over extended period. The study looked at how hands-on repair time is portioned between four primary levels of repair.

- *System Repair*: An Orbital Replacement Unit is replaced with a spare.
- *ORU Repair*: Involves the replacement of an intermediate (I-Level) or “Shop Replacement Unit” (SRU)
- *SRU Repair*: The faulty I-Level SRU is diagnosed and faulty components are replaced.
- *Component Repair*: This is the restoration or remanufacture of single component and is relatively infrequent.

The study examined the proportion of time spent at various levels of assembly. System Repair (ORU Replacement) is performed on orbit and thus System repair times are used as a reference. Compared to a System Level Repair, the time required for ORU Level and SRU level repair are both roughly 5 times longer. The actual replacement of the hardware as a percentage of the overall time required at each level was:

- 19% at System level,
- 20% at ORU level,
- 23% at SRU level.

With roughly 20% of the time at each level spent in the physical repair process the remaining 80% of the time is spent performing pre and post repair processes. The pre-repair activity involves set-up of the equipment and hardware, disassembly, and performing diagnostics. The post repair activity involves reintegrating hardware, testing and revalidation of hardware integrity and even dismantling the set-up.

The data indicates that maintenance beyond the system level will cause a dramatic increase in crew labor, particularly if it extends down to component level replacement. The crew labor penalty diminishes the payload benefit and thus far has been a barrier to lower level repairs. Efforts to reduce crew time should therefore focus on eliminating or reducing tasks surrounding the actual repair. A maintenance strategy that involves hardware replacement below the ORU level will depend on solutions to these issues. Currently, the only known technology program that deals with the full scope of access and integration is the Plug-N-Play Satellite project of the Air Force Responsive Space Technology effort.

IV. Supportability of Missions beyond Earth Orbit

The Constellation Architecture is a combination of vehicles, facilities, Design Reference Missions (DRMs), and mission phases⁵. The Lunar DRMs include the Lunar Sortie Crew DRM and the Lunar Outpost DRMs which include the un-crewed Cargo Altair DRM, the Visiting Lunar Outpost Expedition DRM, the Resident Lunar Outpost Expedition DRM, and the Outpost Remote Operations DRM. The Supportability concept for the Lunar Sortie Crew DRM emphasizes the use of redundancy and high reliability components that require limited maintenance over the

typical 7-day mission. The Altair Sortie Mission carries a maintenance toolkit, which will be based on the Orion capsule toolkit.

Lunar Outpost will be constructed using a combination of several crew and cargo missions. The LSS elements will be delivered using Altair Cargo Landers and the crewed mission durations will increase in length depending on the availability of logistics cargo, such as food, water and clothing. From a Supportability stand-point, the key point is that the availability of Outpost resources such as power, data, communications, launch mass allocation, crew time, and stowage volume is increased over time. The Supportability concept must evolve within these constrained resources and any technology development effort must strive to reduce resource consumption whenever possible. Another key emphasis is to push commonality between the various elements of the Lunar Architecture.

The LSS Maintenance and Repair Concept are separated into two main operations phases: Nominal and Contingency operations. During nominal operations, the maintenance approach is designed to maximize the functional availability of the LSS systems while at the same time reducing the overall supportability burden in terms of logistics mass, volume, crew time for maintenance, and cost. The activities during nominal operations will follow a pre-determined process and schedule that will be managed by the CxP Mission Operations project. During the nominal operations phase, maintenance operations are performed on a continuous basis by the ground crew, surface crew and surface robotic assets. Even if the surface crew is not present, maintenance operations can continue in an autonomous state, especially in the areas of Predictive and Proactive Maintenance where continuous monitoring of the status of LSS hardware is important, especially prior to crew arrival. The second area is Contingency Operations which occurs when, despite the best efforts to anticipate failures through Preventative and Predictive Maintenance techniques, a random failure occurs that may or may not threaten the life of the crew. During Contingency Operations, the maintenance is “reactive” in that the crew will be reacting to an actual hardware failure and the safety of the crew takes the highest priority, and restoring the LSS elements to a functional state in the shortest time possible also becomes a driver.

In order to implement the LSS Supportability Concept, a plan is required whose goal is to significantly reduce the spares and maintenance cargo resupply from Earth. Ideally, the reduced spares and cargo mass reductions come without forcing a significant increase in the consumption of other resources such as crew time, power, and data and communications bandwidth. Because all of these resources are so intricately linked, the main emphasis of pre-System Requirements Review analysis and trades will be to determine the relationships between them and how to best optimize the overall Supportability approach to achieve the best balance between them.

The approach is an evolutionary path that begins with the current ISS support program and culminates in the 500-day Mars mission. Currently, the ISS support program focuses on LRU-level remove and replace procedures which are designed to minimize the amount of crew time required for maintenance. In the ISS plan, failed LRUs are replaced on-orbit and then returned to Earth on the Shuttle for refurbishment and reflight later. After Shuttle retirement, the ISS program will enter a new phase where return of hardware to Earth for refurbishment becomes increasingly difficult. While this has already caused an increase in ISS operations costs due to the need to buy new spares, it will help to prepare for LSS operations since there will be a new emphasis on repair and in-situ diagnostics, test and root cause fault assessment.

The LSS Supportability Concept involves the steps necessary to reduce spares and maintenance cargo mass, and is separated into phases including: the initial ISS support phase using the Shuttle as the primary resupply vehicle (ending in 2010); the ISS support phase beginning with international vehicle support only and then introducing Orion and Commercial Orbital Transportation System (COTS) vehicles as they come on line (2010-2016+); initial lunar orbital flights and Altair Sortie Missions to the Moon (Human Lunar Return in 2021); Lunar Outpost phase (beginning in 2020 and separated into three sub-phases of Construction, Permanent Human Presence and Mars-Forward); and finally the Mars mission phase beginning notionally around 2030. In each of these phases, steps are necessary to approach the end goal of a self-sufficient outpost.

The supportability lessons learned during Lunar Operations will help drive requirements for the future Mars missions, and to fine tune the technologies required for Outpost self-sufficiency. The entire structure of the LSS Supportability Concept is designed to pave the way for future exploration of Mars and other destinations. For the Mars mission, NASA is planning on having one crew and one cargo mission to support a 500-day long-duration stay. The Mars Cargo Lander will pre-position critical cargo which will include not only the spares and maintenance equipment but also scientific exploration cargo, including rovers and other elements, life support gases, crew food and clothing and everything else necessary to sustain life and support exploration. The Mars crew will have to maintain the hardware elements with little support from Earth and strict limits on launch mass and volume.

V. LSS Supportability Needs

Some LSS maintenance and repair needs can be derived from high level Constellation Program documents. Since repair technologies involve the details at the component level, lower level capability documents will be used whenever available. In a recent Technology Prioritization Plan (TPP) for ETDP the LSS Diagnostics, Test & Verification (DTV) and Maintenance & Repair (M&R) capabilities needs were ranked #6 and #7 on the LSS priority list. At the time this roadmap was developed Lunar Surface Systems was still in the architecture development stage and elements were not decomposed below a system level. The Surface Architecture Reference Document (SARD) captures the ground rules and assumptions for scenario development and scenario operational concepts. Although not explicit requirements, these can be used to anticipate capability needs.

At this early stage the project must use analogs to anticipate LSS needs such as Shuttle and ISS and experience. This includes the NASA ISS and STS Logistics Depots experience for lessons learned. The recently completed studies by the Component Level Electronic Assembly Repair (CLEAR) project determined the types electronics used on ISS and the types of problems experienced. They provide an analysis of ISS electronics and contribute to the body of supportability experience and lessons learned.

Lunar missions require LSS to adopt a supportability strategy that is distinctly different from the ISS. ISS and LSS differ dramatically in the types and intensity of activity. LSS will involve more frequent EVAs, more physically intensive operations with severe wear and tear and physical risks. LSS is also composed of independently mobile elements which increase the odds of accidental damage.

A. Needs from LSS Surface Architecture Reference Document (SARD)

Many of the needs, or derived needs, for LSS Maintenance and Repair (M&R) can be found in the Surface Architecture Reference Document (SARD). The SARD is established by the LSS Architecture Team as it develops scenarios or design reference missions to evaluate various vehicle and crew configurations. The SARD includes ground rules and assumptions to help establish boundaries of the architecture trade space. These SARD ground rules explicitly or implicitly affect the Supportability strategy. The ground rules and assumptions related to Supportability are interpreted in terms of supportability capability needs.

The supportability plan as discussed in Section IV is also an appendix of the SARD document. It establishes that logistics beyond Earth orbit needs new capabilities to achieve program supportability, and affordability. Unlike prior plans, this plan involves minimizing logistics dependence rather than growing a logistics infrastructure. The objective is to establish a high level of resource independence which, in turn, requires a new capability strategy.

B. ISS Analog M&R Needs Assessment

The Component Level Electronic Assembly Repair (CLEAR) project was aimed at the development of repair techniques that would enable crews perform effective component level replacement of faulty electronics. This earlier work examined the fundamentals of the basic soldering process in low gravity. It also considered the range of capabilities from basic manual soldering up to an automated apparatus capable of repairing circuits with the latest generation of high density integrated circuits. These capabilities would also be flanked by capabilities to perform diagnostics and tests in support of the repair. These capabilities would need to fit within the payload, resources and crew time constraints of the program.

The work was based on following premises:

1. In many spacecraft electronics assemblies a major portion of the mass is the enclosure (up to 60%).
2. An individual electronic component may weigh between 1/100th and 1/1000th of a complete ORU.
3. Hardware faults are ultimately repaired at the component level.
4. Faulty electronics assemblies are composed of mostly good components.

There are clearly opportunities to reduce logistics mass if a diagnostic and repair capabilities can be compressed into a compact capability. The CLEAR project demonstrated that solder base repair in low gravity is feasible given the appropriate tools and crew training. The project performed an assessment of Constellation Program In-Space Electronic Diagnostics and Repair Needs based on the only practical analog, the ISS. The project examined electrical system drawings and documents from the ISS Vehicle Master Data Base to determine specific materials and processes needed to perform electronic repairs. Further, it considered diagnostic and functional test needs. Rather than simply tally up the conventional equipment the strategy was to examine the signal measurement needs and develop diagnostic and test concept around that information. The study considered the two broad categories of analog (linear) and digital electronics.

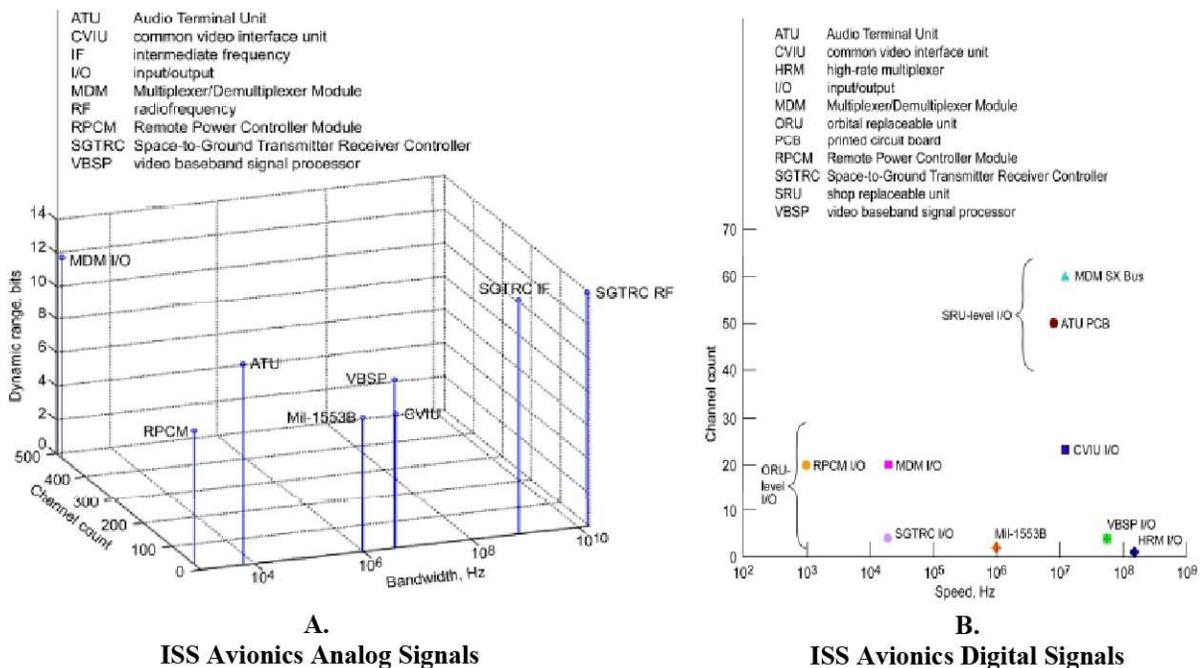


Figure 1. Gamut of ISS Avionics Signal Measurement Needs

Analog covers all non-digital devices used in instrumentation, power modulation, audio, transducer and motor drivers, and radio communications. Analog signals for LSS are expected to be similar to the ISS signals. Figure 1A, characterizes the analog electrical signals of ISS electronics based on three variables Bandwidth, Channel Count, and Dynamic Range. Figure 1B characterizes the digital signals of ISS electronics based on two variables Clock Speed and Channel Count. Digital circuits may involve complex functions but the signals are inherently simple.

Analog signal measurements cover a very broad range of signal types that are difficult to diagnose by embedded techniques and thus requires external diagnostic equipment. To minimize the payload penalty, a *Synthetic Instrument* (SI) approach is recommended. SI employs a single vastly reconfigurable instrument set that provides the capability to emulate (synthesize) many different instruments on demand.

Digital devices are inherently suited for internal Built-in-Test (BIT) capability. Embedded or built in diagnostics reduces the need for external equipment and have little or no impact on weight and volume. The recent trend is toward embedding prognostics at the silicon level that monitors the time dependent degradation that eventually results in an end-of-life failure. Embedding this type of prognostic capability can be used to extend the life of electronics with less dependence on preemptive replacement.

C. Electrical PRACA Analysis:

To address the issue of the types of electrical problems how often they occur, CLEAR examined ISS electrical problem reports. The analysis of ISS Electrical On-Orbit Problem Reporting and Corrective Action (PRACA) Database examined the on orbit electrical problems encountered on ISS. The intent was to determine the percentage of problems that could benefit from diagnostics and the percentage that involve component level repair. Roughly 770 On-Orbit Problem Reports were recorded through a period ending in March 2008 of these 328 were problems associated with electrical systems. A number of patterns emerged from the on orbit PRACAs that suggest certain shortcomings in the current system.

Despite the widespread use of Built-In Test capability there were numerous cases of ambiguity about the root cause of a fault. The study concluded that these BIT capabilities do not extend down to component level where the faults actually occur. Due to ORU remove and replace strategy, the expense of embedding BIT capability much below ORU level is deemed as unnecessary. Once a faulty ORU is removed the root cause investigation is deferred until the item is returned to Earth. This is contrary to the "Proactive Maintenance" approach outlined in Section IV.

For LSS, there is no option to return faulty equipment to Earth and thus the root cause analysis drives the need for component level diagnostics by embedded or external means.

Certain ISS problem reports involved hardware that simply exceeded their expected end-of-life. Most common incidence of EOL hardware faults were in the ISS light fixtures (66 PRACAs) which is considered a "logistics issue" rather than a reliability issue. The logistic solution is to perform preemptive replacements which actually increase the logistics burden by forcing the premature retirement of operating hardware. This implies the need for embedded prognostics to indicate the onset of EOL failures and even indicate life remaining. Embedded prognostic maximizes service life and minimizes preemptive maintenance and logistics.

The study concluded that roughly 63% of the electrical problems would benefit from additional diagnostics, particularly for root cause analysis, and about 42% of the problems could be ultimately resolved by a component level replacement. Many problems are related to operations or software and not hardware, therefore diagnostics does not always result in a repair. For LSS where ground based servicing is nonexistent, diagnostics that can provide insight to the lowest levels is essential to minimizing effort and driving directly to the root cause.

D. Capability Needs Categories

Lunar Surface Systems evaluation of technology priorities ranked the DTV and M&R categories as number 6 and 7 out of many other technology categories. However, scavenging and recycling continues to grow in importance as the lunar architecture studies consider scenarios to reduce costs.

1. Diagnostics, Test and Verification (DTV)

This category addresses the need to diagnose and test a wide variety of potential electrical and mechanical system problems. Effective repair requires initial diagnosis and knowledge of the root cause. Test and Verification are required to verify that repaired hardware is truly functional and suitable to be returned to service.

2. Maintenance and Repair (M&R)

Roughly half the problems on the Space Station involved electrical system problems. Most electrical hardware problems can be traced to faulty components that can be simply replaced. For practical reasons spacecraft mechanical and structural hardware tend to have little or no redundancy. Often there are no spares, particularly, for larger components. Performing an in-situ repair of major mechanical or structural components may be the only option on the Moon. Unlike Space Station, LSS will also have substantial wear and tear problems.

3. Scavenging and Recycling (S&R)

These capabilities are growing in importance as LSS tries to maximize the effectiveness of lunar payloads and minimize the program cost, particularly when a lunar outpost is established. In lieu of a robust logistics system and the uncertainty regarding in-situ material technology the expended descent section of the Altair lunar lander is considered a "resource" for hardware and material logistics.

E. Derived Supportability Capabilities

Table 1 is a listing of needed capabilities derived from interpretation of the SARD Assumptions and Ground Rules, LSS Supportability Concept, CLEAR Project Analysis of ISS, and STS Lessons Learned from Flight Operations and Logistics Depots.

Table 1 Summary of Derived Supportability Capability Needs

Capability Need	Rational
Embedded diagnostics and prognostics employed at lowest levels in electronics.	Many ISS "root cause unknown" results from lack of an ability to identify and isolate a fault below ORU level. Component level Embedded DTV reduces the need and the payload penalties of external instruments.
Employ Synthetic Instrument approach when embedded is not feasible	Certain circuits (particularly analog) have signals or support dependencies that are not effectively addressed by embedded techniques. Synthetic Instruments is intended to minimize the instrument payload penalties of large conventional test equipment. SI exploits advances in FPGA and Signal Manifold technologies.
Embedded structural fault detection and location system.	Flight weight structures are highly stressed and designed with narrow margins. These structures are not damage tolerant and lives may depend on quickly detecting, locating and repairing a fault.
Conductor and connector fault	Conductors (cables and connectors) are significant source of electrical problems

detection, isolation and signal re-routing.	and are vulnerable to operational and environment damage. Conductors in complex harnesses are difficult to repair. Emerging techniques called “signal manifolds” can actively redirect signals through alternate paths around the damage conductor.
Diagnostic RFID, fluid and electrical line locator.	Cable harness and fluid line repair involves locating a specific line among many and is time consuming and prone to risk of further damage. To minimize the disruption and risk, RFID tags can be used to quickly locate a specific line at key access points.
Remote In-Situ Calibration	DTV and Repair equipment must be properly calibrated. Without an option for returning equipment to Earth for calibration, Remote or in-situ calibration is the only viable option.
Accessible Enclosures for ease of assembly, diagnostic, repair with minimum loss of integrity	Space systems are difficult to access for diagnostics and repair. An enclosure that unfolds to allow diagnostics and test without violating system integrity dramatically simplifies repair operations. It is also highly applicable to scavenging.
Reconfigurable electronics	Reconfigurable electronics allows us to use scavenged hardware as spares to reduce logistics.
Component Reparability & Scavenge-ability	In-situ repair is viable if the materials selected are suited to scavenging, repair and reuse with minimum processing.
Non-Contact Measurement	Measurements made by optical or imaging methods are essential to support diagnostic and repair of hardware with a minimum set of instruments. Non-contact methods also avoid risk of damage and wear in harsh process environments.
Metal Weld Repair	Major structures are not supported by spares and must be repaired in-situ. Electron Beam technology can weld repair cracks, rejoins or reinforces broken metal hardware and even upgrade utility by weld-on features.
Material Cutting and Sizing	Repairs exploits scavenged materials require cutting & trimming techniques suitable for extracting a variety of materials of varied shape and size.
Manual and Automated Electronic Component Repair	Electronics assemblies are almost entirely built by solder processes. Depending on complexity solder repairs may be done manually or by automated equipment.
Surface Repairs, in situ restoration of damaged hardware surfaces	Many mechanical faults involve damaged surfaces. Surface damage in flanges and hatches cause leakage. Rotating shafts, bearings, and motors are vulnerable to surface damage. Repair must also treat surface properties: (Hardness, corrosion resistance, conductivity)
Materials Scavenging, recycling and fabrication feedstock generation	Scavenging materials and reusing them requires converting the reclaimed material into a suitable feedstock that is versatile and minimizes the material logistics infrastructure.
In Situ Fabrication Capabilities	To exploit scavenged or recycled materials requires a space compatible fabrication process capable of producing usable end products with little or no process consumables and no post processing.

VI. LSS Supportability Strategy

The Vision for Space Exploration involves an “expansion process” but NASA budgets are not expanding and are, in fact, only a fraction of the Apollo Program. Budget constraints require NASA to keep a program affordable and sustainable because once the capability is in place the ongoing operational cost is a constraint to future capabilities. This has been the experience with the Space Shuttle and the International Space Station where the operations cost of the established capability limits the ability of NASA to pursue its next objective.

There is concern that a Lunar Outpost will likewise restrict the future of space exploration. The technologies that support the Lunar Outpost must minimize support cost but also provide a high value or return on investment (ROI). A high ROI not only helps reduce constraints on future programs but may also reduce the costs of Mars exploration.

A. Strategy: Resource Independence

This section defines a strategy that considers the overall goal, considers constraints and the lessons learned and the needs determined in the previous sections. The strategy involves developing capabilities based on technologies that can reduce or eliminating the dependency on imported hardware, material and operational resources. It exploits the environment and the material properties and behaviors in the lunar environment. The supportability strategy is to build capabilities that achieve a high level of logistics resource independence and minimize the cost of sustaining operations.

1. *Low Consumable Dependencies*

Lunar environment itself can be considered the equivalent to a resource that can be used to reduce process support needs. For example, soldering and welding repair operations can be performed in a vacuum without flux agents by exploiting the lunar environment and employing technologies that can pre-clean a surface without consumables. Reducing dependency on a critical process consumable also reduces risk. If the supply of a consumable is exhausted the process is halted and the capability is lost. This may cripple a crew's ability to repair a problem with the possible loss of capability or even loss of mission. Process technology that is not bound to a complex set of logistic consumables is innately robust.

2. *Resources from Scavenging and Recycling*

In the long term, many materials can be extracted from the lunar surface by In-Situ Resource Utilization (ISRU). In the near term, portions of the lander can be scavenged and reused for spares or secondary applications. Scavenging can be done at various levels of assembly from LRU to component level and even the raw materials can be scavenged or recycled for various applications.

3. *Vitamin Logistics*

The term "*vitamin technology*" was coined to describe an approach to lunar logistics where payload mass is minimized and value is maximized by importing small amounts of high value technology and combining it with low value in situ materials and technology⁶. This is based on an analogy from biology where bulk consumption of foods must be augmented with small amounts of essential "vitamins" to assure health. It addresses the reality that capabilities of independent operations still benefit from importing small amounts of vital materials. By focusing costly logistics payload capacity on high value technology and materials while exploiting the low value bulk materials available from scavenging, recycling and in-situ sources; logistics may be much more effective. A microprocessor or field programmable device can be considered a vitamin technology. Further, a high value "*vitamin material*" may be an alloying element or special plating material that greatly enhances the properties of simple bulk material.

4. *"Bootstrap" Capability Expansion*

Certain technologies are attractive because they are versatile enough to expand capabilities in a "bootstrap" strategy. A bootstrap capability provides the flexibility to exploit resources and expand its initial capability. This implies some form of fabrication technology that can convert hardware assets and materials into a new product. Such a product would include tools, fixtures, and other aids that are not otherwise part of a tool inventory. An example of a bootstrap capability for the lunar environment may be using scavenged hardware to construct simple resource gathering tools, build fixtures that aid in fabrication and repair, construct simple structures that support energy collection and storage, or convert surplus tanks or logistics modules into LSS Depot applications.

5. *Capabilities consistent with the Resource Independence Strategy*

The supportability lessons learned, supportability capability needs and the resource independence strategy can be distilled into general technology characteristics that best meet the needs.

- **Ease of Use:** Low demand for crew, operations, and engineering support resources (operational effectiveness).
- **Lunar Environment Compatibility:** This reduces containment needs, resource consumables and maximizes the utility in the lunar environment.
- **Resource Effectiveness:** Minimizes logistics resources dependency and maximizes exploitation of available or in-situ resources
- **High Utility:** Provides or supports a wide variety of applications included bootstrap expansion.
- **Risk Impact:** Reduce risk or empower the crew to effectively respond to risk.

B. Scavenging & Recycling Impact on Supportability

Scavenging & Recycling (S&R) improves “Return on Investment” of Supportability is more *deterministic*. That is, DTV and M&R technology normally sits and waits for something to break. Whereas, the technology employed as part of S&R operations will have specific roles. DTV will be used to assess the initial serviceability of the scavenged hardware, evaluate repairs or modifications, and perform functional tests to verify the hardware is suitable for service. The M&R equipment is used directly in assembly and repair or reconfiguration of scavenged hardware. Scavenging thus provides a specific and scheduled role for the technologies and places a quantifiable value on the supportability technology.

1. Consumables Scavenging

LSS plans to “scavenge” residual propellants (H₂ & O₂) for power and water. This capability is already covered under the In-Situ Resource Utilization (ISRU) project and is not included in this roadmap.

2. Hardware Scavenging

This involves extracting serviceable hardware from the lunar lander or other spent flight hardware. The priority is to employ scavenged hardware as spares. The hardware spares can be acquired at various levels from LRU level, SRU level, and down to the component level. The next priority is to reuse hardware for secondary applications including the bootstrap expansion of outpost infrastructure and a potential LSS Depot capability.

Hardware scavenging has an impact on DTV needs. DTV technologies can be used for diagnostics and evaluation of scavenged hardware. It can be used for performing functional test and verification of scavenged hardware prior to reuse. Hardware scavenging also has an impact on M&R needs. M&R capabilities support the disassembly of LRUs for lower-level spares can be used in the repair and reconfiguration of hardware.

3. Materials Scavenging & Recycling

Materials extracted from landers, logistics modules, and reclaimable waste can be used as material for repair and fabrication. Materials extracted from landers can serve as feedstock for repair and fabrication. This, in turn, drives the need to embed scavenge-ability into hardware and materials selection. Materials scavenging and recycling is a primary driver of advanced process technologies including Electron Beam and Ion Beam based processes.

A Mars mission will be highly dependent on material recycling, and the proposed resource independence strategy of the Lunar Outpost will demonstrate material recycling technologies.

It should be noted that materials recycling has drawn significant attention in recent years. The LSS S&R technologies may have important environmental-social-economic spin-off potential as “green technologies” that may provide a tangible return on investment in terrestrial applications.

C. Develop Embedded and Process Capabilities

Maintenance and repair are commonly viewed as involving external processes. However, there are many opportunities to embed a capability into hardware. By embedding as much capability into the design of the flight hardware as possible the program can minimize the up-mass of external equipment. Further, the features that assure that hardware is repairable by in-situ processes must be done in the initial design. Therefore embedded and process technologies are co-dependent, and development of one influences the other.

Process and embedded technologies have different development criteria and are addressed in the following sections. These lower-level criteria will be consistent with the development strategy, and used to screen the initial set of technologies and used in down-selecting candidate technologies. The criteria will be balanced so that negative and positive aspects keep the evaluation simple and minimize the need for weight functions. Criteria will need to be reviewed and refined by stakeholders. In many cases, the selection criteria may also serve as the basis for *Key Performance Parameters* (KPP) which are used to monitor the progress of the technology development.

D. Technology Infusion

Generally, Technology Readiness Level (TRL) level 6 is considered mature enough for infusion into a space flight program⁷. Currently, the schedule shows that the first Altair vehicle will fly in 2021. Technology for Altair must be at TRL-6 by the time the preliminary design review is complete. Although the criteria for selecting a capability are driven primarily by needs, there may be multiple technology options available. Technology selection requires further criteria that consider the needs in a context of constraints or operational drivers, such as, size, weight power (SWP), crew operations, and training⁸. In sections 7 and 8 these criteria are identified and will be used to evaluate the candidate technologies. The criteria will be further refined and technologies will be characterized in the formulation phase by feasibility studies and technology assessments.

The technology development funding for Constellation is very constrained and not all technologies can be funded. All technologies will be screened by a process that involves evaluating the following criteria.

- **TRL (Technology Readiness Level):** Current Technology Readiness Level (1-6) where TRL-6 is regarded as the technology infusion point.
- **SWP Cost: Size, Weight and Power Impact:** Increase/decrease in payload and related cost
- **Crew Operational Cost:** Impact on crew time, training and engineering support cost that offsets payload impact.
- **Risk Impact:** How does the technology reduce risk or provide a response to risk
- **Down Selection:** Technical issue or competing technology would prevent the technology from being adopted that is not a programmatic Schedule or Cost issue.

VII. Embedded Supportability Technologies

Supportability technologies can be designed-in or “embedded” into the flight hardware to minimize the need for external hardware with little impact to weight and power. Embedded technologies however impose added development risk in the host hardware and must be integrated into the flight hardware development schedule. Embedded technology should be at high TRL for infusion into the Altair flight vehicle development path. The development of embedded supportability technologies has a direct impact on the process technology development. In some cases, embedded minimizes the need for process equipment while in others the embedded technology assures the effectiveness of the external process technology.

A. Embedded Technology Development Criteria

Derived from general needs, lessons learned, and specific assumptions and ground rules from the Surface Architecture Reference Document, this section describes the capabilities or special properties that can be embedded into systems. The following list represents the capabilities needed and evaluations of embedded technologies will consider how well these needs are met. The criteria below are intended to assure that the technologies are consistent with the Supportability Strategy.

1. *Access for Maintenance, Repair and Scavenging*

Embedded technologies need to assure that hardware is accessible for maintenance, repair and scavenging. Rationale: This includes considering the time effectiveness of manual and automated access with minimum violation of system integrity. Depot and ISS flight experiences indicate that crew time to extract LRUs, hook up equipment de-integrate, access components, re-integrate and test assemblies far exceeds the time involved in the actual component repair. This is expected to be the same for scavenging operations. Therefore, embedding features that enhance accessibility and preserve integrity also improve supportability.

2. *Embedded Diagnostics*

Embedded technologies need to provide diagnostic capabilities from the system down to component level. Rationale: The ISS PRACA report history indicates that current built-in-test capability on ISS provides limited insight into problems below the ORU level. There are a substantial number of “unknown root cause” statements in the ISS PRACA system that, currently, can only be resolved by returning equipment to the Earth. Component level embedded diagnostics reduces external equipment, and speeds problem isolation. Further, it also reduces the time and cost of unneeded replacement due to root cause ambiguity or misdiagnosis.

3. *Embedded Prognostics*

Embedded technologies need to provide prognostics capability from the system level down to component level. Rationale: Component level embedded prognostics reduce external equipment, reduce ambiguity, and speeds problem isolation. Prognostics are aimed at detecting time dependent (aging effects) that will ultimately end the life of otherwise reliable hardware. End of life is dependent on variations in the original manufacturing and service life history. The preemptive “time based maintenance” approach means the service life is cut short. An embedded means of tracking life experience and degradation is needed. Embedded prognostics devices can track life experience by sharing the same experience and same degradation environment. Specific internal indicators can be used to alert the system and predict an end of life failure. Thus as a form of “condition based maintenance” it eliminates the need for wasteful preemptive replacement without the risks of running the system to failure.

4. *Common Components and Interfaces*

Embedded technologies need to provide a high level of commonality that minimizes M&R equipment needs, operational resources needs, component spares required. Rationale: Commonality has elevated importance when scavenging of flight components as spares. The ability to repair with scavenged components will depend on the ability to transplant components from one system to another.

5. *Adaptable, Reconfigurable Hardware*

Embedded technologies need to provide flexibility or innate reconfigure-ability to support applications beyond the original flight function. Rationale: Re-using flight hardware may require reorganization of internal functions or combining basic functions with other hardware (and functions) to provide new capabilities. This has implications for software and interconnection designs. In some cases, the adaptability can be seen as an alternative to imposing commonality.

6. *Scavengable Components*

Embedded technologies need to provide an ability to safely extract components and reuse them without substantial loss in reliability. Rationale: Scavenged components intended as spares will still need to provide a high level of reliability. Designers will need to consider how a component can be mounted that will allow it to be extracted, stored, and reused in a condition suitable for reuse as a spare or for new applications

7. *Scavengable Recyclable Materials:*

Embedded technologies need to provide materials that are compatible with the lunar environment and can be scavenged and recycled with a minimum set of processes. Rationale: The success of the supportability strategy depends on developing lunar compatible materials and processes that do not require massive equipment or imported process materials. This means limiting the choice of materials which may have an impact on vehicle payload performance. The trade-off between maximum performance and reusability must consider the supportability impact.

8. *De-rated Design for Repaired or Scavenged Hardware*

Flight hardware needs to provide a capacity to operate in a de-rated mode that allows scavenged or repaired hardware to operate under less stress and provide extended useful life. Rationale: Repaired and scavenged hardware cannot be as thoroughly tested as the original acceptance tests and thus there is uncertainty about reliability. Designing hardware to operate in a de-rated mode lowers stress, adds margin and improves reliability and operational life.

B. Embedded Technology by Capability Category

In Figure 2 the three main capability categories in embedded technologies are further decomposed to capability sub-categories. The capability needs are defined for each sub-category and “candidate” technologies are briefly discussed. Note that in some cases the sub-categories are better described as hardware or material properties rather than capabilities.

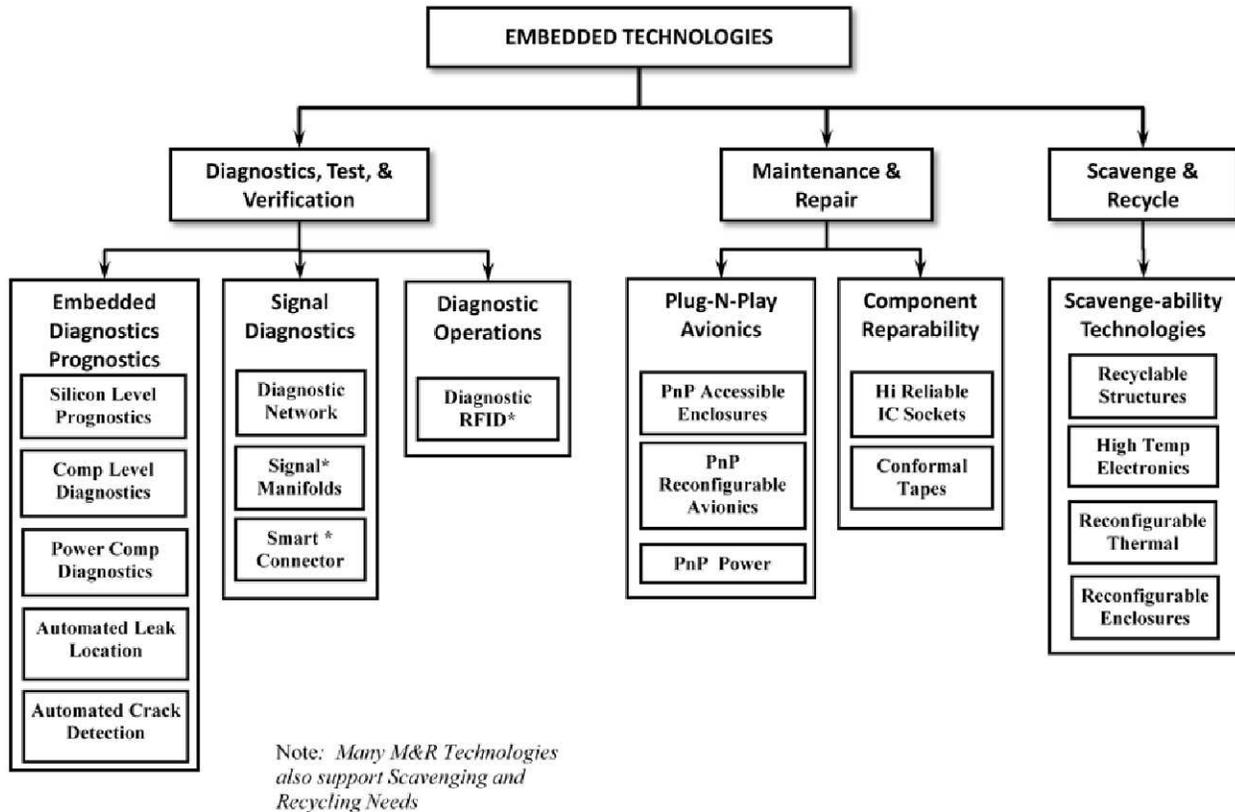


Figure 2. Embedded technology needed for LSS Supportability

C. Embedded Diagnostics, Test & Verification Category:

1. Embedded Diagnostic and Prognostic Capabilities

This capability provides the diagnostic and prognostic capability from ORU level down to component levels. The techniques can assist in detecting and isolating faults and problems that evade system level detection. Further, new techniques permit the prediction of the ultimate end of life at the silicon level for electronics. For large structural components techniques are needed that assist the crew in detecting and locating dangerous cabin leaks and potentially catastrophic structural cracks.

- *Silicon Level Prognostics:* Embedded in electronics, features at silicon level that serves as a “canary device” that provides an early detection of age dependent degradation and indicates end of life.^{8,9,10}
- *Component Level Diagnostics:* Embedded in electronics, techniques that detects lead cracking in large IC packages such as Ball Grid Array (BGA) packages.¹²
- *Power Component Diagnostics:* Ring-down technique to expose degradation of power components¹³.
- *Automated Leak Location:* Acoustic sensor network for detecting and quickly locating cabin pressure leaks.
- *Automated Crack Detection:* Acoustic sensor network for detecting structural cracks.

2. Embedded Signal Diagnostic Capabilities

Diagnosing and testing of hardware is often impeded by complex connectors and wiring harnesses and the need to build custom test adapters for each application. Analog wiring is particularly troublesome because each line may have unique signal properties and be susceptible to interference and loss of signal integrity. There are multiple options around this problem. Converting analog to digital not only reduces sensitivity but allows data to be sent via high speed serial data links that use common conductors, connectors, and interface protocols. If plug-n-play features are embedded, then hardware can be disconnected and reconnected elsewhere in the system assuring portability. This portability is particularly important for scavenging and reuse of flight hardware. The “Smart Transducer”

approach extends network connections and flexibility down to the individual device level. By tapping into multiple networks the transducer has a fault tolerant way of sending and receiving data. The penalty of this Smart Transducer is the added complexity and need for a Smart Transducer Interface Module (STIM) and an internal Transducer Electronic Data Sheet (TEDS).

Many electronic problems only appear when the units are physically interconnected and operating. Often it is necessary to attach multiple instruments to observe signals. In some cases, it is necessary to inject a stimulus signal and observe a response. To diagnose these problems requires an ability to tap into signals between units without violating system integrity or distorting signals.

- *Diagnostic Networks:* Embeds networking at the transducer level and provides a means to reconfigure avionics to isolate devices and perform ad-hoc in-circuit testing. It employs new IEEE 1451 “Smart Transducer” standards where each device includes a Network Capable Application Processor (NCAP), a Smart Transducer Interface Module (STIM) and an embedded Transducer Electronic Data Sheet (TEDS).¹⁴
- *Smart Connector:* May be used as an embedded or external technique. Provides signals monitoring of integrated systems and reduces the number of specialty test connectors while reducing fault ambiguity. It may be further enhanced if combined with “signal manifold” technology.
- *Signal Manifolds:* Employs MEMS technology that provide complex signal routing on impedance “tunable” lines for accurate in-situ diagnostics and tests without violating integrity or requiring insertion of test adapters. This also allows for remote signal rerouting without physical intrusion.¹⁵⁻¹⁷

3. Diagnostic Operations Capabilities

These capabilities address the physical aspect of diagnostics and repair operations. Locating and repairing faulty wires, components, and fluid lines is impeded by the large number of lines packed into spacecraft and the ambiguous markings used.

- *Diagnostic RFID:* Embedded RFID tags can assist in the physical location and replacement of the correct components or lines and even provide ancillary data to support tests.¹⁸

D. Embedded Maintenance & Repair Category:

1. PnP Avionics Capabilities

This is an adaptation of capabilities developed by the Air Force Research Lab as part of the PnP Satellite Program that employs multiple technologies to rapidly integrate a satellite in 6 days. The capabilities combine Structural, Avionics, and Power accessibility in one design. PnP Avionics includes enclosures with integrated hinged walls where avionics boxes can be literally unfolded without disconnecting or violating the system integrity. It includes PnP self-organizing network connections; it also involves power utilities that are embedded in both the network connections and the structure. Further development is needed to adapt these technologies for fault tolerant human rated applications.

- *PnP Accessible Enclosures:* Highly accessible enclosure assemblies with unfold-able or hinged structural joints. This structure allows the integrator to structurally disconnect panel hinge-points of a cube shaped enclosure so that it can lay flat for ease of access.¹⁹
- *PnP Reconfigurable Avionics:* Plug-N-Play network that automatically configures the connection and reads the IEEE 1451 Smart Sensor Electronic Data Sheet.¹⁹
- *PnP Embedded Power:* Embeds power distribution ports in enclosure structural panels.²⁰

2. Electronic Component Reparability Capabilities

This need involves developing components that are designed to permit field repairs with minimum processing. This includes eliminating features that impede access, removal, and reinstallation of components. This could include developing a removable conformal tape that could eliminate conformal coatings used on electronics. This includes reintroducing the use of IC sockets designed to be vibration and shock resistant and provide a near tool-less method of replacing integrated circuits.

- *Hi Reliable IC Sockets:* Simple repair by special IC mounting sockets allows replacement of Integrated circuits with simple hand tools.²¹

- *Low ESD Conformal Tapes*: Simple low static discharge conforming tape permits removal and reapplication of conformal protection without physical damage or hazardous chemicals. This tape may be derived from high temperature low ESD tapes used in circuit fabrication.²²

E. Embedded Scavenge & Recycle Category

1. Scavenge-Recyclable Capabilities

This sub-category involves embedding properties that supports scavenge and recycling capabilities. They improve hardware and material scavenging by either simplifying the scavenge process or by improving the reusability of hardware. For materials, scavenging and recycling implies selecting materials that can be processed in the lunar environment. For example: high temperature electronics are intended to address the reusability of scavenged electronic components by eliminating the need for central thermal control system.

- *Recyclable Structures*: Structures made of materials that are easily recycled for new applications.
- *High Temperature Electronics*: High temperature tolerance eliminates or reduces the need for heat sinks and cold plates and may eliminate the need for a central thermal control interfaces and improve portability.
- *Reconfigurable Thermal Control*: Removable reconfigurable avionics thermal control that provides portability and less dependence on centralized active thermal control.
- *Reconfigurable Enclosures*: This is an extension of PnP avionics that involves developing avionics enclosures that can be decomposed into panels and reused to create new avionics assemblies.¹⁹

F. Embedded Technology Preliminary Characterization

A preliminary characterization of the “technology candidates” in terms of technology infusion is shown in Table 2 below. This can be considered an initial screening based on commonly used parameters described in section VI.

Table 2 Embedded Technology Preliminary Characterization

Technology	TRL	SWP Cost	Crew Cost	Risk Impact or Utility	Selection Issues
<i>Silicon Level Prognostics</i>	5	No Impact	reduced	Reduces unexpected EOL, Enables in-situ root cause analysis	None
<i>Component Level Diagnostics</i>	5	No Impact	reduced	Enables In-situ root cause analysis	None
<i>Power Component Diagnostics</i>	4	Low	reduced	Reduces unexpected EOL, Enables In-situ root cause analysis	Redundancy
<i>Automated Leak Location</i>	3	Low	reduced	Enables rapid response to cabin air leakage	Integration
<i>Automated Crack Detection</i>	2	Low	reduced	Enables rapid response to structural cracking event	Tech Maturity
<i>Diagnostic Networks</i>	4	Low	reduced	Provides automated internal isolation and test of circuits	Determinism
<i>Smart Connector</i>	4	Low	reduced	Reduces ambiguity, prevents R&R errors	None
<i>Signal Manifold:</i>	4	Low	reduced	Enables signal rerouting around failed connections	Configuration Control
<i>Diagnostic RFID</i>	4-5	Low	reduced	Reduces errors and explicitly identifies and tracks hardware.	optical methods
<i>PnP Accessible Enclosures</i>	5	Medium	reduced	Enables simple physical access, reduces violation of system integrity	Encapsulation requirements
<i>PnP Reconfigurable Avionics</i>	5	Low	reduced	Enables rapid integration of new functions, reduces integrity violation	Determinism, Redundancy
<i>PnP Embedded Power</i>	4	Low	reduced	Enables rapid power integration	Determinism, Redundancy
<i>Hi Reliable IC Sockets</i>	2-3	Low	reduced	Enables rapid R&R of electronic components	Vibe specs

<i>Conformal Tapes</i>	2-3	Low	reduced	Enables rapid restoration of conformal coatings	Reliability
<i>Recyclable Structures</i>	2	Medium	reduced	Enables Structural Elements to be reused by simple processes for repairs	Weight
<i>High Temperature Electronics</i>	3	Improves	reduced	Possible elimination of active thermal control	Tech Maturity
<i>Reconfigurable Thermal Control</i>	3	Improves	reduced	Enables greater LRU portability	Tech Maturity
<i>Reconfigurable Enclosures</i>	4	Medium	reduced	Enables enclosure reassembly for new applications	Tech Maturity

G. Embedded Development Schedules^{††}

Embedded technologies impose some added development risk in the host hardware and must be integrated into the flight hardware development schedule. Because the primary vehicle of interest is the Altair lunar lander, the schedules for all embedded technologies are virtually locked-in with the vehicle schedule, as illustrated in Figure 3. The technologies are aimed at specific capabilities within the three main categories. There is limited overlap or competition between the embedded technologies. The primary competition is between embedded and the equivalent process technology. A selected embedded technology may reduce the need for a process technology. In other cases a process technology is dependent on certain embedded features. Therefore, embedded technology selections are expected to impact the selections of Process Technology.

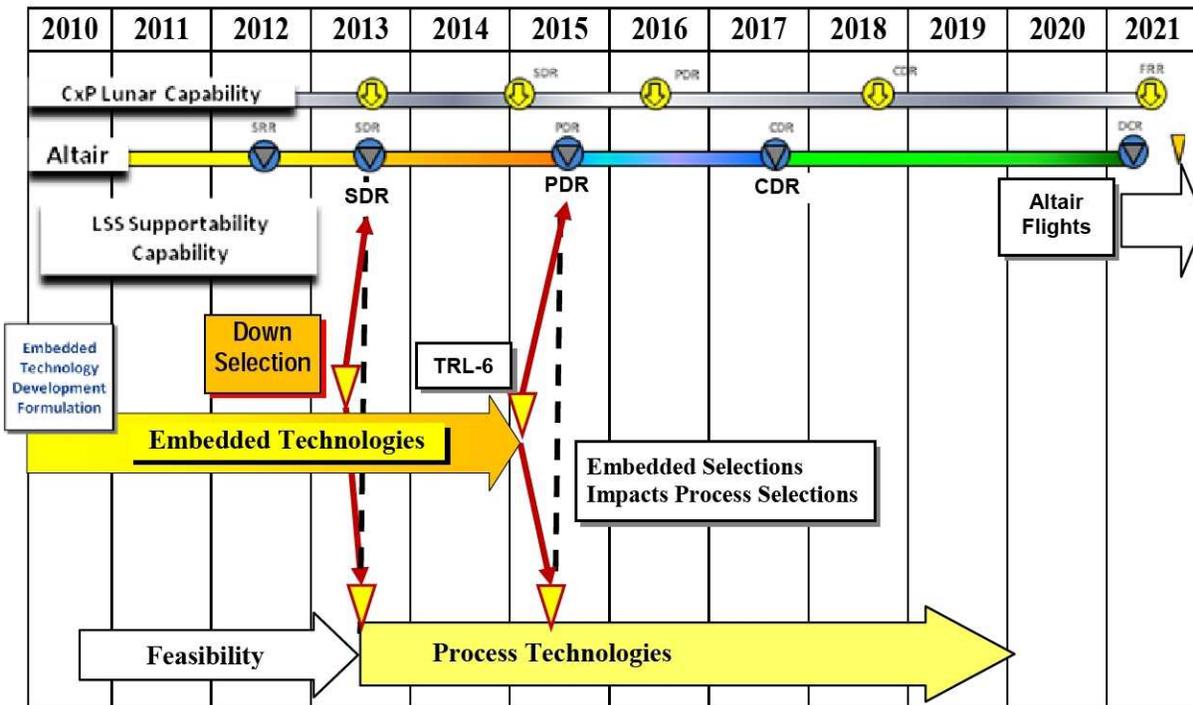


Figure 3. Embedded Capabilities Development Schedule

H. Embedded Technology Development Cost Considerations

Of the capabilities listed many involve a distinct technology that is embedded or added to the flight hardware design. In some instances the capabilities can be interpreted as design features or properties that are incorporated with little impact on the overall vehicle development. Some demonstration may be required to validate the TRL. Certain capabilities such as Air Force Research Lab Plug-N-Play Avionics technologies or Navy's NAVAIR Avionics Technology programs may be acquired through a cost sharing collaboration with the Air Force and Navy.

^{††} Recently updated program schedules indicate that Altair flights begin in 2021.

Note that the ETDP role in embedded technology development ends when the technology is infused and the flight program becomes responsible for flight development.

VIII. Supportability Process Technologies

Derived from general needs, lessons learned, and specific assumptions and ground rules from the Surface Architecture Reference Document, this section describes the capabilities needed and the technologies intended to meet them. Process technologies are external to flight hardware and development is driven by end applications. The development schedules for process technology are similar to independent payloads and are not expected to be on the flight vehicle development path. As described in the previous section, the development of process technology is somewhat dependent on selections made in embedded technology. If there is technical or program reason not to adopt an embedded solution, then an external process may replace it. In other cases, a process technology may depend on the design materials selection and changes in materials will directly impact the viability of a specific process.

A. Process Capability Criteria

Process technology will need to be demonstrated independent of the flight hardware and may include demonstration aboard ISS. The criteria below are intended to assure that the technologies are consistent with the Supportability Strategy.

1. Environment Compatibility Criteria

A process that is compatible with the space environment eliminates the complexities of preserving materials and hardware in space. Environment compatibility minimizes process support and containment equipment and, in turn, simplifies operation and logistics. Consistent with the Supportability Strategy, developing process technologies that are compatible also reduce resource dependency. Process compatibility is primarily an issue of base material and process material compatibility. Processes that require an atmosphere impose added burdens on the crew cabin environment; instead processes should be selected that are suited to the lunar environment.

2. Process Dependency Criteria:

Process dependency may be defined as the need for external infrastructure, consumable material resources, and pre and post processes and equipment, crew or robotic operation support, or dedicated process containment required to perform processes. Dependencies are contrary to the supportability strategy of resource independence. They are also a measure of the process's logistics and operational complexity. A thorough breakdown and description of these dependencies is a system engineering task that is needed for an informed technology evaluation.

3. Resource Effectiveness Criteria

The supportability strategy based on resource independence requires that the resources imported from Earth be minimized, and effectively used. In addition, the strategy requires developing capabilities to exploit available resources effectively. As capability builds, the long term goal is to switch from an entirely logistics based resource consumption to in-situ resource consumption. The use of scavenged hardware and materials from flight systems is a transitional capability that bridges the gap between pure logistics and in-situ resource utilization

4. Process Utility Criteria

The process utility is intended to select technologies that provide the greatest possible utility from a small set of capabilities in order to achieve the Supportability strategy. Process Technologies will be evaluated for their ability to support multiple applications across the DTV, M&R and S&R categories. The utility evaluation also evaluates the technology for utility in both internal (IVA) and external (EVA) applications. The evaluation assesses the utility as a manual, automated or robotic process. The utility evaluation of a process determines the potential to expand or to "bootstrap" an existing capability. For example: technologies that can produce tools can effectively expand capabilities without additional payloads.

Table 3 Process Technology Evaluation Criteria

Environment Compatibility	Dependency	Resource Effectiveness	Utility
Gravity	Infrastructure	Common Logistics Resources	Utility Across Categories
High Vacuum	Logistics Resource	Scavenged Hardware	EVA & IVA Utility
Thermal	Pre and Post Process	Scavenged Materials	Manual, Robotic Utility
Radiation	Operational	Lunar Environment	Capability Expansion
Dust	Containment		

B. Process Capabilities

The three main capability categories in process technologies are further decomposed to capability sub-categories. The capability needs are defined for each sub-category and “candidate” technologies are shown.

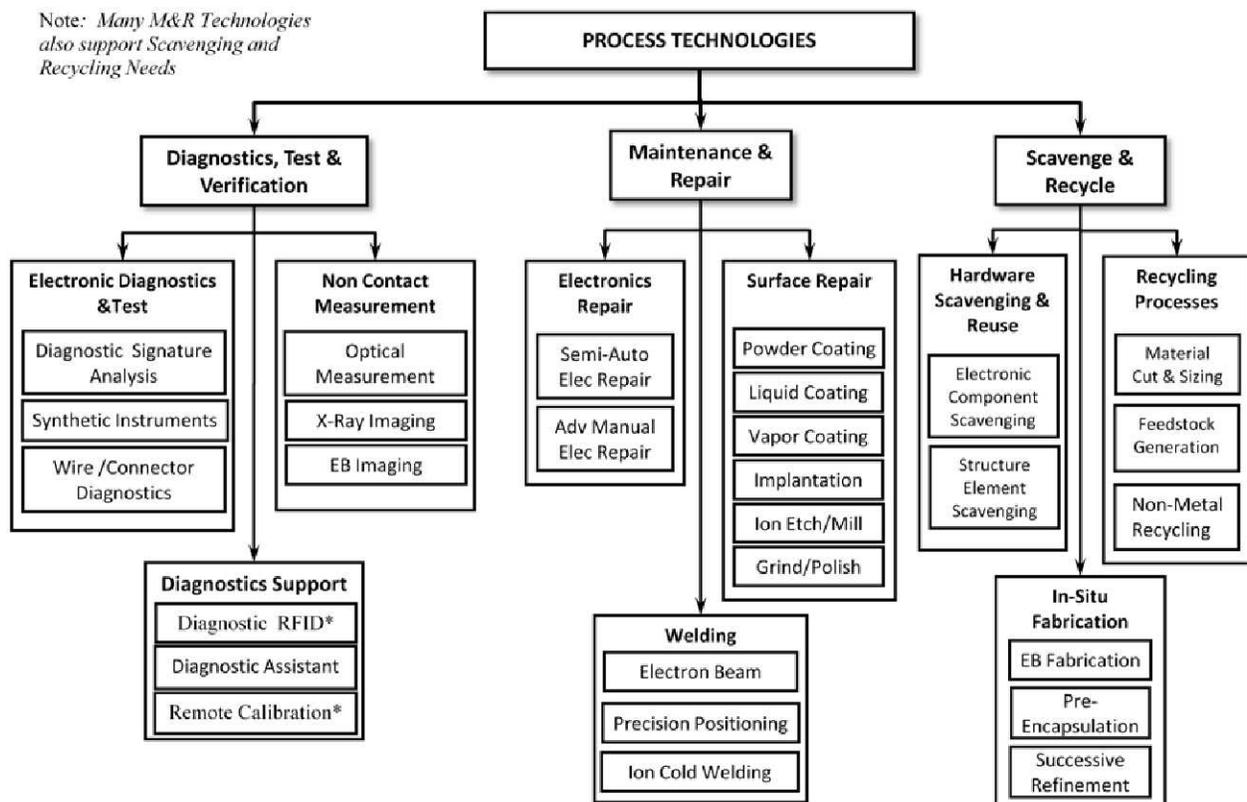


Figure 4. Process technology needed for LSS Supportability

C. Diagnostics, Test & Verification Process Category:

This capability provides the diagnostic and prognostic capability from ORU level down to component levels. The techniques can assist in detecting and isolating faults and problems that evade system level detection. The technologies shown here are external processes and in some cases overlap the capabilities of the embedded technology. Unlike embedded, however, process technology is more flexible with broader application and utility. Process DTV technologies may also serve as back-up whenever embedded DTV is rendered inoperative. The result of selecting an embedded technique will impact the related process technology, but it is unlikely embedded solutions will eliminate processes entirely. The following describes the technology candidates for three DTV Process Sub-Categories:

1. *Electronic Diagnostics & Test Processes*

This subcategory is very important because electronics have many built-in functions and special instruments are the only way to observe these functions. Even mechanical systems rely on electronics for remote command, control, and data acquisition.

- *Diagnostic Signature Analysis:* Diagnostics based on graphical trace comparison of a known good signature against a suspect signature that allows unskilled users to locate circuit faults. Tech development involves broadening the range by integrating complex signature analysis.²³ **Error! Reference source not found.**
- *Synthetic Instruments:* A technique using advanced FPGA techniques to replace conventional instruments with a single compact unit capable of “synthesizing” various instruments on demand. Tech development aimed at eliminating analog dynamic range and signal routing limitations.²⁴
- *Wire Connector Diagnostics:* Methods of evaluating wire harness and connector integrity rapidly using combined electrical and physical response to an injected signal.²⁵

2. *Non- Contact Measurement*

This subcategory is primarily aimed at measuring mechanical hardware dimensions and internal material properties. Non-contact, optical, dimensional measurements and various imaging technologies can make measurements with fewer tools that also do not interfere with the processes they support. Further, they provide measurement of key internal properties and can detect hidden flaws.

- *3D Optical Measurements:* Optical measurement of 3 dimensions and surface properties can eliminate a variety of unique measurement tools.
- *X-Ray Imaging:* Used to provide internal flaw detection, measure internal dimensions, and provide materials properties. It has been used to investigate mechanical problems non-intrusively
- *Electron Beam Imaging:* Electron Beams have an extreme range of imaging scales and are compatible with the lunar environment. Integrating E-Beam imaging with welding and fabrication technology is possible.

3. *In-Situ Diagnostics Support*

This subcategory involves technologies specifically aimed at assisting the user (crew). It includes a local node attached to the Constellation Command, Control, Communications and Information (C3I) infrastructure and for diagnostics support. This capability will also include local information libraries and data archives that can support the user in case communications are lost. The RFID and digital user assistant devices are at fairly high TRL level and should be linked to Altair for early applications. Remote calibration, however, is a problem with no clear solution and warrants further investigation.

- *Diagnostic RFID:* Exploits RFID to help identify and track repair hardware and assist in physically locating and identifying faulty LRUs and specific harness cables.¹⁸
- *Portable Electronic Diagnostic Assistant:* Based on U.S. Navy NAVAIR unit that provides the user interface and various maintenance libraries that are automatically synched and refreshed and with ground based sources, including synthetic instrument programs, hardware manuals, "gold" signature data, and crew training and refresher media. This portable assistant (laptop or PDA) will also provide wireless LAN access.²⁶
- *Remote Calibration:* Calibration is a supportability infrastructure issue that demands an innovative solution that eliminates the need to physically return instruments to Earth for calibration.

D. Maintenance & Repair Process Category

This category is composed of three subcategories; electrical repairs, weld repairs, and surface repairs. The capabilities will also apply directly or support scavenge and recycling processes. Repair capability will be needed, as early as, the first Altair mission. The following describes the technology candidates for three M&R Process Sub-Categories:

1. *Electronics Repair Processes*

Although there is a vast array of electronic functions in space systems there is only one primary way of mounting components, specifically, soldering. Most soldering needs can be covered by manual and automated process.

- *Semi-Automated Electronics Repair:* A concept developed by the CLEAR project and derived from industrial automated workstations that can be programmed to support diagnostic probing and then perform component level R&R using a solder reflow process. This may also support electronics scavenging.²⁷

- *Advanced Manual Electronics Repair*: Special tools, fixtures and prepackaged material kits may be used to compensate for relatively low user soldering skills. Such kits would bridge the gap between current ISS tools and the semi-automated reflow process.^{28,29}

2. *Welding Repair Processes*

Welding has vast applications in both repair and fabrication of mechanical and structural hardware. Directed energy beam techniques are normally automated or performed robotically. E-beam welding surface quality often eliminates post weld finishing. Ion Cold Welding is a metal bonding technique invented specially for high vacuum applications.

- *Electron Beam Welding*: Only electron beam based welding technology is viable from an environment and consumables aspect. E-Beam welding can often weld materials without additional feedstock. Due to precise beam energy and steering control, welds are often very smooth. For wider range of motion a precise robotic motion is needed. E-beams are not generally considered as a manual method.³⁰
- *E-Beam Precision Positioning*: E-Beam welding has built-in beam steering capability that provides wide versatility. However, many welding applications require complex 3D weld paths that require robotic manipulation. Mobile equipment based robots will need to be augmented with high levels of path stability to maintain the E-beam precision welding capability.
- *Ion Cold Welding*: This technique is for thin sheet or foils materials and exploits the natural tendency of ultraclean metal surfaces to bond without high temperatures. Ion engine derived etching technique strips oxides and contamination from the surface and allows simple mechanical pressure to bond surfaces.³¹

3. *Surface Repair Processes*

LSS hardware is expected to experience a great deal of surface damage due to operations in the lunar environment. Repair of surfaces due to wear, scratches, gouges, contamination and erosion will affect mechanical, structural, optical and even electrical hardware. Damage on critical mating surfaces such as hatchways or pressure system flanges may prevent sealing and may result in loss of critical resources. Robotic and mobility systems will likely experience surface abrasion damage on rotating and sliding surfaces on shafts and bearings. Damage due to rocks, abrasive sand, and dust may be a cause of frequent mechanical maintenance.

Surface damage often involves damage to the coatings that provide protection or special surface property. Coating repair processes may include non-volatile powder or materials like liquid metals. Some coatings are applied as thin molecular scale films by thermal vapor or ion techniques.

- *Powder Coating Processes*: For surfaces with relatively thick coatings such as paint, repairs may be applied by an electro-statically charged thermally fused powder or atomized liquids. Electrostatic transfer of powder is used in virtually all copiers and laser printers and can be applied to high vacuum operations. Lasers and electron beams have been used to thermally fuse powders which eliminate the need for masking materials.
- *Liquid Droplet Coating*: Coatings of non-volatile liquids can be applied using high vacuum adaptations of ink jet technologies. These techniques can precisely place pico-liter drops of material with an accuracy of an ink jet printer. At least three droplet techniques can handle temperatures of metals from solder to aluminum.³²
- *Vapor Coatings*: Electronics and optics make extensive use of thin film coatings applied by vapor deposition. The two primary types are Thermal and Sputtering vapor deposition. Thermal vapor deposition simply vaporizes a material and condenses it onto the surface. Ion Sputtering transfers molecules from source to a substrate surface. Sputtering provides finer control and operates at much lower temperatures and can be used to apply metal, polymer, and even ceramic coatings.^{33,34}
- *Regolith Abrasives*: This technique may be an effective alternative to machine finishing that exploits lunar regolith. Relatively low torque, low vibration, and lubricant free operation, makes it a potential high vacuum replacement for conventional machining techniques.
- *Ion Implantation*: Ion implantation is a surface treatment that implants material at or below the surface. This technique can change the fundamental properties of the base material. It is widely used in the creation of semiconductors. It has been used to harden tool steels as a substitute for heat treatment. Ion implantation is one way to restore the properties to materials altered by processes like welding.³⁵

- *Ion Etch*: Ion etching has been used for both electronics and MEMS fabrication. Ion etching has been used to remove surface oxides and contaminants allowing metals to be cold welded together. (ref Patent) Ion etching has also been coupled with electron beams in electronics manufacturing.³⁶
- *Ion Milling*: Ion milling employs directed ion beams similar to electron beam technology and is a direct descendent of ion engine technology. Ion milling can drill very deep holes and precisely cut hard machine tool materials with cutting edges with unequaled sharpness. Ion technology is also effective on ceramic and glass materials. It is a mask-less process that can operate on surfaces and on full 3D objects.³⁷

E. Scavenge & Recycle Process Category:

This process category includes hardware scavenging, materials scavenging and in-situ fabrication. Hardware scavenging is likely to be the earliest form of scavenging. Operations would likely employ the very same tools used in maintenance including diagnostic and test equipment. Some specialized tools may be needed for special application such as scavenging large tanks or rocket engine hardware. The propulsion systems have some intriguing potential for reuse including power generation, ISRU processing, and short range robotic "hopper" applications that use reaction control thrusters. The unmanned cargo landers provide a full array of avionics including power distribution, communications, navigation, controls and data handling systems. The cargo landers provide the best opportunities for scavenge-able spares.

As hardware spare inventory is satisfied there will be a surplus of duplicate hardware. With no specific applications, this hardware may be scavenged for its material content. Material scavenging only has value if it is reformed into usable product. Materials scavenging (recycling) will require special processes that convert materials into a suitable intermediate feedstock. Recycling is expected to be process and power intensive and may become significant after the Lunar Outpost is complete.

Note that most of these capabilities are currently considered to be "technology gaps". This means that there are no specific technology solutions to meet the capability. The following describes the technology candidates for three S&R process sub-categories.

1. Hardware Scavenge & Reuse Processes

This subcategory involves removing hardware and processing at various levels of assembly down to component level. This includes processing that will make the hardware suitable for spares. Reworking or reconfiguring hardware for secondary applications will involve equipment already described for repair and maintenance applications.

- *Electronic Component Scavenging*: In faulty electronic assemblies most components are still good. When surplus electronic LRUs become available the components may be extracted as spares. Components like integrated circuits are best handled by an automatic solder reflow capability with pick and place component extraction. The Semi Automated Electronics Repair apparatus described in the M&R category provides a suitable capability.
- *Structure Element Scavenging*: Structural scavenging is aimed at acquiring elemental structural shapes, fasteners, and hardware for spares or new applications. Safely separating welded assemblies may require special cutting technologies. Candidates may include lunar oxygen based plasma or oxygen assisted E-beam cutting tool. Lunar regolith may serve as a working media in an electrostatic driven hypervelocity abrasive particle jet cutting tool.

2. Material Recycling Processes

Recycling requires a series of processes to decompose a material and convert it to a usable feedstock. The processes needed depend on the materials selected. Metals offer the greatest versatility but composites may make up a considerable portion of the final vehicle weight. Altair material decisions will dramatically affect recycling technologies.

- *Material Cutting and Sizing*: Many materials can be reused "as is" but must be cut free from the parent structure and trimmed to a usable size for reapplication. Cutting processes must provide wide utility without a large mechanisms or consumable cutting edges. Multi-purpose E-beam, ion beam or plasma techniques along with hypervelocity abrasive particle jets may be viable.

- *Metal Feedstock Generation:* This technology converts scavenged metals into feedstock for repair and fabrication. The simplest approach may be to simply melt metal (potential e-beam application) and create a metal powder feedstock by a combination of ultrasonic and electrostatic means.
- *Non-Metallic Recycling:* In addition to metals the lander will be composed of composites, glass, ceramics and polymers. Each has different recycling methods and level of difficulty. The amount of a given material type available may determine if recycling is worth the development costs. At this point the material make up of the vehicle is uncertain.

3. In-Situ Fabrication Processes

In-situ fabrication subcategory poses the most challenge but also provides the greatest payoff in achieving the Supportability strategy. Without fabrication the payoff for scavenging and recycling cannot be realized. To eliminate the need for a massive manufacturing infrastructure tool-less techniques or Free Form Fabrication (FFF) technology is essential. The current state of the art in FFF does not produce finished parts. The technology below is intended to advance FFF to the point where it is possible to produce useful products without post processing.

- *Electron Beam FFF Processes:* There are two techniques that appear to be strong candidates for lunar applications. Both employ electron beam technology and both provide a fully dense metal product. Electron Beam FFF (EBF3) is a derivative of electron beam welding and Electron Beam Melting (EBM) is derived from early powder sintering technologies. EBF3 has been tested in zero-g aircraft flights and has a higher TRL level. EBM appears to outperform EBF3 by producing products that more closely represent the final product. EBF3, however, has greater control of the feedstock, much greater multi-axis mobility, and demonstrated the ability to perform post processing. EBF3 has demonstrated low sensitivity to gravity and thus is more robust.³⁸
- *Pre-Encapsulation:* This technique minimizes or eliminates the need for post processing by using pre-machined parts that are embedded into the product. By encapsulating a precision feature, the fabrication process can form the bulk material around the prepositioned part without distorting it. Similar techniques have been used for casting and conventional welding. The approach is consistent with the "vitamin technology" aspect of the Supportability strategy by exploiting a small amount of high value encapsulated hardware and bulk scavenged materials.
- *Successive Refinement FFF:* Most FFF techniques employ an open-loop approach to build products in a series of 2D planes. Variations in material feedstock delivery or fusion with the underlying form create irregularities. Without refining or correcting the accumulated flaws, the resulting product is equivalent to a rough cast part requiring post process machining. Elimination of post process machining and its resource and compatibility issues is essential to achieving the Supportability strategy. Successive refinement approach provides constant monitoring of the true shape and combines additive and subtractive techniques that provide closed-loop control and corrects accumulating deviations. By changing scale to smaller additive and subtractive increments down to the molecular scale it will be possible to produce highly accurate products. This capability is a hybridization of electron beam technology, materials deposition technologies, and extractive ion etching and milling technologies.

F. Process Technology Preliminary Characterization

A preliminary characterization of the “technology candidates” in terms of technology infusion is shown in Table 4 below. This can be considered an initial screening based on commonly used parameters described in Section VI.

Table 4. Process Technology Preliminary Characteristics

Technology	TRL	SWP Cost	Ops Cost	Risk Impact and Utility	Selection Issues
<i>Diagnostics Signature Analysis</i>	4	Low	reduced	Enables crew in-situ fault finding with minimum training	None
<i>Synthetic Instruments</i>	3	None	reduced	Provides compact in-situ fault diagnostics and post repair test	None
<i>Non-Contact probing</i>	3	Low	reduced	Diagnostic probing without damage to circuit coatings	Effectiveness
<i>Conductor Diagnostics</i>	3	Low	reduced	Provides wire and connector fault diagnostics	Effectiveness

<i>Optical Measurement</i>	3	Low	reduced	Simplifies dimensional measurement.	Tech Maturity
<i>X-Ray Imaging</i>	4	Medium	Medium	Non Intrusive mechanical fault diagnostic tool	Wt, Power
<i>E-Beam Imaging</i>	3	Medium	Medium	Precision flaw detection and surface evaluation	Tech Maturity
<i>Diagnostic RFID</i>	5	Low	reduced	Rapid ID and Location of components and lines	None
<i>Diagnostic Assistant</i>	4	Low	reduced	User tool for Prognostic and Diagnostics analysis	None
<i>Remote Calibration</i>	2	Medium	reduced	Enables calibration without returning tools to Earth	Tech Maturity
<i>Adv Manual Electronics Repair</i>	4	Medium	Low	Enables repair of wiring and large components	Effectiveness
<i>Semi-Auto Electronics Repair</i>	3	Medium	Medium	Enables repair of high density electronics	Weight
<i>Electron Beam Welding</i>	6	High	High	Enables repair of mechanical& structural components	Wt & Power
<i>Precision Positioning</i>	4	High	Medium	Precise handling for field repairs.	Wt & Power
<i>Ion Cold Welding</i>	4	Medium	Medium	Simplified welding of thin sheet stock.	Effectiveness
<i>Power Coating</i>	3	Medium	Medium	Repairs thick film coatings	Tech Maturity
<i>Liquid Droplet Coating</i>	3	Medium	Medium	Precisely repairs coatings without masks	Tech Maturity
<i>Vapor Coating</i>	3	Medium	Medium	Provides thin film repair for optics, Solar cells and electronics	Effectiveness
<i>Ion Implantation</i>	4	Medium	Low	Restores special surface properties to repaired hardware	Tech Maturity
<i>Ion Etch & Milling</i>	3	Medium	Low	Provides precision etch and milling of small components	Tech Maturity
<i>Abrasive Grind & Polish</i>	1	High	Medium	Exploits regolith cleaning, leveling and scratch removal	Effectiveness
<i>Electronic Comp Scavenging</i>	3	Medium	Medium	Automatically recovers electronic components for spares	Weight
<i>Structure Element Scavenging</i>	2	High	High	Enables Scavenging of structural hardware	Wt & Power
<i>E-Beam Fabrication</i>	5	High	High	Enables fabrication of replacement components	Effectiveness
<i>Pre-Encapsulation</i>	2-3	Medium	Medium	Enables precision devices to be embedded in FFF products	Weight
<i>FFF Successive Refinement</i>	2	High	Medium	Provides finished FFF products without post processing	Tech Maturity
<i>Material Cutting & Sizing</i>	2-3	Medium	Medium	Extracts and sizes scavenged stock by beam or particle techniques	Tech Maturity
<i>Metal Feedstock Generation</i>	2	High	High	Enables fabrication from scavenged metals	Tech Maturity
<i>Non Metallic Recycling</i>	2	High	High	Enables recycling of Non-Metallic materials.	Tech Maturity

G. Process Technology Development Schedules^{††}

The schedule for Supportability process technology is more complex than embedded and involves an incremental phased development. Certain technologies are driven by early needs where others are driven by the available infrastructure required to support them. All technologies are expected to achieve TRL-6 well before Altair's first flight. Further refinement of the schedule requires project formulation process that follows the delivery of this technology roadmap.

^{††} Recently updated program schedules indicate that Altair flights begin in 2021.

1. Phased Technology Development Milestone Rationale:

Supportability roadmap completion is followed by the Supportability Technology Development Formulation process in FY2010. Process technologies are external to flight hardware. They are not expected to be on the flight vehicle development path and are more consistent with an independent payload schedule. Process technologies are aimed at providing specific capabilities and development is driven by end applications. Although focus has been on Lunar Surface Systems, the first user is expected to be Altair and certain capabilities will be tailored for Altair. These process technologies follow the Altair schedule and there are roughly ten years available from now to the first landings of Altair. Other capabilities will be developed on schedules consistent with the build-up and completion of the Lunar Outpost.

Rather than show a development schedule for individual technologies, Process technologies are grouped into three development paths based on the point where the capability is needed. The three capability milestones are Altair First Flight, Outpost (delivery of Hab1), and Outpost Complete.

2. Altair Supportability Capabilities (Altair first Crewed Flight Milestone: 2021)

- Basic DTV and M&R capabilities will be provided to the first crewed mission.
- Capabilities are limited to contingency tools due to vehicle space and weight constraints and the expendable nature of the vehicle. This group will include handheld diagnostic tools and manual repair tools.
- Technology development should achieve TRL-6 at 4 years before the Altair Flight Readiness Review

3. Outpost Supportability Capabilities (Delivery of Habitat 1 Milestone: 2025)

- Most of DTV and M&R capabilities will be delivered and hardware scavenging capability will be phased-in following Hab-1 delivery.
- Capabilities are scaled to suit the permanent nature of the habitat and the ability to accommodate DTV and M&R equipment in a workstation. Phasing is affected by the availability of LSS infrastructure and accommodations of the Lunar Outpost and thus delivery spans the time between Hab-1 delivery and Outpost Complete.
- Hardware scavenging capabilities will be provided to allow the crew to exploit lander hardware for spares.
- Hardware scavenging capabilities phasing depends on the build-up of the Outpost infrastructure and on how aggressively the program exploits lander hardware.
- Technology development should achieve TRL-6 at 2 to 3 years before the Altair Flight Readiness Review

4. Outpost Complete Supportability Capabilities (Outpost Complete Milestone: 2027)

- All DTV and M&R capabilities will be in place.
- Hardware scavenging technology will be operational and scavenging operations for spares will have begun.
- Materials Scavenging & Recycling and in-situ Fabrication are phased in
- Material Scavenging & Recycling capabilities are energy intensive so the Lunar Outpost must have an adequate power infrastructure.
- Accumulation of an inventory of landers is needed to make materials scavenging feasible.
- Technology development should achieve TRL-6 prior to the Altair Flight Readiness Review

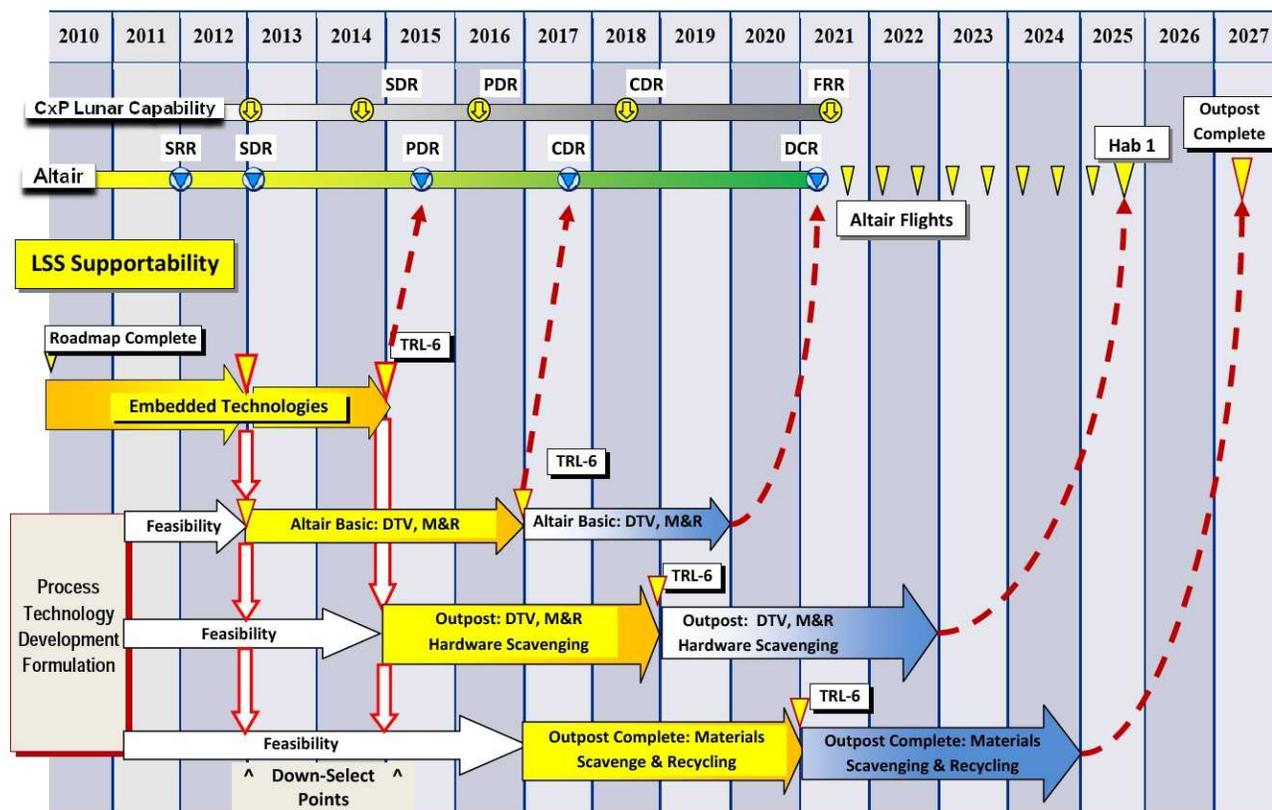


Figure 5. Process Technology Development Schedule

5. Technology Decision Gates

The decision gate where the first process down-selection occurs is directly linked with the embedded down-selection point prior to Altair SDR. The TRL-6 milestones shown in Figure 5 are where technology infusion occurs. In many cases the embedded and process technologies are complementary and the down selection point for process technologies is affected by the infusion of the embedded technologies. If an embedded technology is dropped the related process technology may be expanded. Conversely, successful infusion of embedded technology may result in de-scoping or dropping a process technology.

The schedule shows that at the TRL-6 milestone the technology may be adopted by the program for flight development, or dropped. The schedule is intended to provide three years of further development beyond TRL-6 to achieve full operational readiness two years before flight. This allows the hardware to be fully integrated into the vehicle.

The schedule also shows that a number of technologies for later phases are carried in a low intensity “Feasibility Phase” where technologies are carried under a system level feasibility analysis. Many may be developed by other organizations or by Small Business Innovative Research (SBIR) funding. For each incremental technology group, the development starts with Authority-To-Proceed and groups are phased on 2 year increments but individual technology schedules may vary.

H. Development Cost Considerations

Of the capabilities listed many involve a distinct process technology that is new and enabling for lunar applications. The majority of the processes already exists in industry, but may be rarely used because high vacuum support system requirements are very expensive to build, maintain and tend to impede flexibility. These high vacuum based processes require an equipment and infrastructure investment that must be amortized over many units. This is why these processes rarely appear outside the high value, high production rate facilities of the

electronics industry. In the lunar environment, these same technologies are free of the high vacuum equipment may be a simple low mass, power efficient, and comparatively low cost alternative to converting a conventional process.

IX. Summary of Embedded and Process Incremental Capabilities

Capabilities are grouped into four technology increments and linked to Constellation milestones:

A. Increment 1

Currently all embedded technologies are intended for Altair First Flight, (2021). Embedded technology TRL-6 and infusion by Altair and should be achieved by Altair PDR (2015). The embedded technologies are aimed at providing multiple supportability capabilities without increasing size weight and power of the flight hardware yet decreasing crew time required for DTV, M&R and S&R operations. For practical reasons not all the technologies will be applied to Altair. Most technologies are expected to apply directly to Lunar Surface Systems. Scavenging however, drives the need to assure that Altair has compatibility, commonality, access and internal features that support reusability.

B. Increment 2

For process technologies limited set of DTV and M&R tools will be available for Altair First Flight, (2021). The TRL-6 infusion point is set to support the Altair CDR (2017). Altair, as an expendable spacecraft, has limited need and accommodations for spares or repair capabilities. For crew safety, a basic set of readily available tools and diagnostics equipment will be needed. The diagnostic and test may be as limited as a single portable synthetic instrument.

C. Increment 3

Outpost Hab-1 Delivery, (2025) a set of DTV, M&R and Hardware Scavenging equipment will be available two years before flight. The TRL-6 infusion point is at Launch– 6 years (2019). The actual delivery of complete DTV and M&R capabilities will likely be spread over several flights during the build-up of the lunar outpost. With the accumulation of spent landers hardware scavenging may begin to create an inventory of spares at various levels of assembly.

D. Increment 4

Outpost Complete, (2027) the Material Scavenging and Recycling technologies will be delivered 2 years before flight. The TRL-6 infusion point is at Launch– 6 years (2021). By the time of Outpost Complete the scavenging of Altair hardware may likely exceed the expected spares needed. The surplus hardware can be scavenged for its material content. Eventually, the capability to convert the materials to feedstock will be needed as a resource for extended repair and component fabrication.

X. Conclusion

In preparing this document the project was provided information by various subject matter experts and contributors representing NASA centers, NASA contractors, the U.S. Navy, the U.S. Air Force and industry. Supportability strategies have been discussed from Apollo through STS, the Russian MIR and ISS. Lessons learned have been provided by the US Navy, ISS Flight Operations, NASA Shuttle Logistics Depot and NASA Space Station Depot. LSS needs were established using various sources including the Surface Architecture Reference Document, CLEAR Project Documents, and needs derived from lessons learned. The LSS Supportability plan for missions beyond Earth orbit has been provided by Lunar Surface Systems Supportability.

In the LSS Supportability Plan and the LSS Supportability Technology Strategy the goal of achieving a high degree of resource independence was established as the focus for defining the criteria and selecting the technologies. From this goal and the lessons learned submitted by contributors, two types of technologies were established. Specifically, *Embedded* and *Process* technology types that were defined based on the method of technology infusion. Both types have three primary application categories, specifically; Diagnostics, Test & Verification, Maintenance & Repair, and Scavenging & Recycling.

Embedded and Process technologies are distinctly different in how they are infused into the program and thus each has different development cycles. Embedded technologies are directly linked to the Altair development milestones. Meanwhile, Process technologies are linked to their end application and have a more schedule latitude. Embedded technology by ETDP ends when the technology is infused or adopted by the Altair program. Embedded

technologies must be at TRL level 6 by Altair Preliminary Design Review (PDR). Embedded technology leads process technology development on the overall schedule and may have a direct impact on the selection and development of process technologies. Therefore, embedded technology down-selection milestones are linked to the process technology down-selection milestones. Finally, the technology development has been organized in four waves or increments.

The Supportability Technology Roadmap has identified a wider set of capabilities and technologies beyond maintenance and repair. In many ways this effort is the first exposure of the underlying complexity involved in establishing a human presence on another world. It is likely that only a portion of these technologies will prove viable. In some areas only a capability is defined and may represent a gap in the current technology base. Some near term capabilities will exploit technologies developed by other programs. Some downstream capabilities envisioned, such as scavenging and recycling, will require a long term development commitment but may ultimately provide the greatest return on investment by providing a bootstrap capability. Overall, these capabilities will provide a suitable capability for Mars while helping to minimizing the operational costs of lunar exploration. The Supportability Technology Roadmap is a living document that is expected to evolve. This Supportability Technology Roadmap is expected to help shape the operational infrastructure of human exploration.

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XII. References:

¹NASA, Mission Operations Directorate- Space Flight Training Division, *International Space Station Familiarization Training Manual*, ISS FAM C TM 21109, June 3, 2004

²NASA, *Surface Architecture Reference Document (SARD)*, Version 3.4, September 12, 2008.

³Larson, W., Pranke L., "*Human Spaceflight: Mission Analysis and Design*", McGraw-Hill, New York, 1999

⁴Goetter, C., *Contemporary On-Orbit Maintenance Philosophies*, Submitted in Partial Fulfillment of the Requirements of MAS 604, Human Factors in Aviation/Aerospace Industry, Embry-Riddle Aeronautical University (Houston Resident Center), March 1999

⁵Green, J., Spexarth, G., "A Mars-Forward Approach to Lunar Supportability Planning" AIAA-2009-6427 [to be published]", Casitair Consulting, Tampa, FL, 2009

⁶Freitas Jr, R., *Advanced Automation for Space Missions*, Proceedings of the 1980 NASA/ASEE Summer Study, 1980.

⁷Mankins, J., *Technology Readiness Levels*, White Paper, NASA Advanced Concepts, Office, Washington DC, 1995

⁸NASA/SP-2007-6105, *NASA Systems Engineering Handbook: Technology Assessment*, Washington DC, 2007

⁹Goodman, D., Wood, S., "Return-on-Investment (ROI) for Electronic Prognostics in High Reliability Telecom Applications", IEEE 1-4244-0431-2/06, 2006

¹⁰Goodman, D., US Patent 7239163 – "Die-level process monitor and method", 2007

¹¹Goodman, D., US Patent 7271608 – "Prognostic cell for predicting failure of integrated circuits", 2007

- ¹²Hofmeister, J., Judkins, J., Ortiz, E., Goodman, D., "Real-Time BIST Detector for BGA Faults in Field Programmable Gate Arrays (FPGAs)", Ridgetop Group Inc. Tucson, AZ, 2006
- ¹³Ridgetop Group Inc., "RingDown™ Power Prognostics", 05/09 DS01_RingDown_OV_revD", Ridgetop Group Inc. Tucson, AZ, 2009
- ¹⁴Mark, J., Hufnagel, P., IEEE 1451.4 Standard Working Group, "IEEE 1451.4 Standard for Smart Transducers", IEEE Standards Association, 2004
- ¹⁵Lyke J.C, US Patent 6667873 - Adaptive Manifold, 2003
- ¹⁶Lyke, J.C., US Patent 6958664 - Variable permittivity structure based on micro-electromechanical systems (MEMS) 2005
- ¹⁷Lyke J. C., US Patent 6148399 - Advanced Instrument Controller, 2000
- ¹⁸Fink Patrick et al, "RFID Needs for NASA Applications", CANEUS Workshop 2007
- ¹⁹Arritt, Brandon J. et al, Development of a Satellite Structural Architecture for Operationally Responsive Space, 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 2008
- ²⁰McNutt C.J., Vick, R, Whiting, H., Lyke, J., Modular Nano-satellites – (Plug and Play) PnP CubeSat, AIAA, 7th Responsive Apac Conference. April 2009
- ²¹Dozier, US Patent 6913468, Method of removably mounting electronics components to a circuits and sockets formed by the methods, 2005
- ²²3M Corp, "Clean room High Temperature ESD Tape", 3M product literature, St Paul, MN, 2006
- ²³Smith C.S, "Fundamentals of Signature Analysis: In depth overview of Power Off testing using Analog Signature Analysis", Product Literature, Huntron Inc. July 2009
- ²⁴Lupinetti, Francesco: "New Synthetic Instrumentation methods Solve Tough System Level Test Problems", Electronic Design, 2008
http://www.aeroflex.com/ats/products/prodfiles/articles/8888/2170E_ED_AERO_ePrint.pdf
- ²⁵Madaras, Eric I, Anastasi, Robert F., US Patent 6810743 - "Non-destructive evaluation of wire insulation and coatings", 2004
- ²⁶Shannon, R.; Quiter, J.; D'Annunzio, A.; Meseroll, R.; Lebron, R.; Sieracki, V., "A systems approach to diagnostic ambiguity reduction in naval avionic systems", Autotestcon, IEEE, 2005
- ²⁷Struk, P.M., Oeftering, R.C. Easton, J.W., and Anderson, E.E., "Semi-Automated Diagnosis, Repair, and Rework of Spacecraft Electronics," 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 7-10, 2008, AIAA-2008-1130.
- ²⁸Pettigrew, R.D., Easton, J.W., Struk, P.M., and Anderson, E.E., "In-Flight Manual Electronics Repair for Deep-Space Missions," *Aerospace Conference, 2007 Institute of Electrical and Electronics Engineers (IEEE)*, March 3-10, 2007
- ²⁹Lyke, J. C., US Patent 6539618 - Ball grid array tool, 2003
- ³⁰Taminger, K. M. B., and Hafley, R. A., "Characterization of 2219 Aluminum Produced by Electron Beam Freeform Fabrication," *Proceedings of 13th SFF Symposium*, Austin, TX, pg 482-489 (2002).
- ³¹Sater, B., US Patent 4245768- "Method of cold welding using ion beam technology", 1981
- ³²Oeftering, R., NASA, U.S. Patent 5,772,479, "Directional Electrostatic Accretion Process Employing Acoustic Droplet Formation", 1998
- ³³Goebel, D., Katz, I., "Fundamentals of Electric Propulsion – Ion and Hall Thrusters", Wiley & Sons, Hoboken, NJ, 2008
- ³⁴Remnev, G.E. et al, "High intensity pulsed ion beam sources and their industrial applications", *Surface and Coatings Technology* 114 pg 206–212, 1999
- ³⁵Shrivastava, S, "Hardening of steel by boron ion implantation dependence on phase composition", *Vacuum* vol. 47, No. 3 pg 247-249, 1996
- ³⁶Sater, B.L., US Patent 4245768, "Method of cold welding using ion beam technology", 1981
- ³⁷Ishitane et al, US patent 723579, "Focused Ion Beam Apparatus", June 2007
- ³⁸Taminger, K. M., Watson K. J., Hafley R. A., US Patent 7168935 – "Solid freeform fabrication apparatus and methods", 2007